

International trade and tourism in a CO₂-constrained world

Philip Krammer

University College London
2017

Thesis submitted for the degree of Doctor of Philosophy
in Energy and Economics.

Declaration

I, Philip Krammer confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

.....

Abstract

The introduction of market-based measures to combat CO₂ emissions from international transport will affect countries with a higher dependence on international trade and tourism to a greater extent than those relying more on domestic markets. This thesis quantifies the resulting changes in real income in the trade and tourism sector in 123 countries. It consists of three main parts.

The first part explores the relative price changes of operational mitigation strategies in ocean freight versus air freight, based upon a logit model that is embedded into a trade model with homogeneous firms. Results indicate that the slow steaming of ships could reduce CO₂ emissions from international trade by a significant amount (50%) and with only little impacts on welfare (-0.6%).

The second part derives—in the absence of dedicated theoretical frameworks—a gravity model of international tourism. Estimating the demand model yields a price elasticity of four, which is similar to estimates in international trade. Unlike in trade however, the calculated welfare gains vary widely across countries and can be as high as 54% for small island developing states (SIDS).

The third part combines the tourism model and a simplified version of the trade model into a multi-sector, multi-country general equilibrium model to examine the economic impact of a global bunker fuel levy in the international air and maritime transport industry. The resulting economic cost of reducing one tonne of CO₂ in both industries corresponds to approximately \$400 in global value added. A carbon price of \$150/tCO₂ could raise all of the \$100 billion of global climate finance needed, while 318 Mt of transport related CO₂ could be abated cost-effectively each year. This scheme would result into a nonrecurring drop in gross world product of 0.13% and, except for SIDS and landlocked countries, be non-discriminatory against developing countries.

Acknowledgements

I am grateful to Professor Andreas Schäfer, whom I have been fortunate to have as my thesis advisor. His expertise and advice added considerably to my graduate experience and his encouragement and substantial support have been very helpful throughout this research project. I am very grateful to Professor Costas Arkolakis for his advice on the trade model and to Professor Samuel Kortum for his advice on the tourism model. I thank my PhD examiners, Professor Thierry Mayer and Professor Michael Grubb, for constructive criticisms and valuable comments and suggestions that helped to improve the content and presentation of my dissertation. I would like to express my appreciation to Dr. Tristan Smith for thought provoking questions, which regularly opened new perspectives and improved the quality of my work. I would also like to thank Dr. Nicholas Lazarou for many helpful and interesting discussions and comments.

Much of the research summarised in this thesis has been presented at conferences and seminars including the 2017 RES PhD Meetings, the 2017 RES Symposium of Junior Researchers, the 2016 Yale Department of Economics seminar series, the 17th Annual Conference of the European Trade Study Group in 2015, and the UCL Energy Institute seminar series. I would like to thank all participants for helpful discussions and comments.

Large parts of this research project were completed while I was visiting the Department of Economics at Yale University. I gratefully acknowledge the department's hospitality as well as the support I received from the UCL Doctoral School, the UCL Energy Institute and the Yale Department of Economics.

This work was supported by the Engineering and Physical Sciences Research Council [grant reference number 1345976]. I gratefully acknowledge the financial support.

I thank Professor Peter Guthrie, Professor Dieter Scholz, and Professor Peter Horst for their support and encouragement to undertake a PhD. The past four years have been an extremely rewarding experience for me.

Above all, I would like to express my deepest gratitude to my parents for their faith in me and enduring encouragement throughout my career.

Contents

List of Figures	8
List of Tables	9
Nomenclature	12
1 Introduction	16
1.1 Context	17
1.2 Problem statement	18
1.3 Aim and Scope	20
1.4 Significance of the study	21
1.5 Overview of the study	23
2 Literature review	24
2.1 Trade	24
2.2 Tourism	33
2.3 International transport and the environment	34
2.4 Legal dimension of international transport policy	37
3 Methodology	42
4 Model of international trade	47

4.1	Background	47
4.2	Theoretical framework	51
4.3	Data	62
4.4	Trade and mode-specific preferences	66
4.5	Trade, transport and prices	73
4.6	Counterfactuals	79
4.7	Summary	88
5	Model of international tourism	90
5.1	Background	90
5.2	Theoretical framework	93
5.3	Data	102
5.4	Tourism, geography, and prices: a first look	105
5.5	Estimating the tourism equation	108
5.5.1	Tourism, transport and prices	109
5.5.2	Global tourism patterns	113
5.5.3	Tourism competitiveness	118
5.6	Counterfactuals	122
5.7	Summary	128
6	International trade and tourism in a CO₂-constrained world	129
6.1	Theoretical framework	130
6.2	General equilibrium model	138
6.3	Data and input parameters	144
6.4	Policy scenario	147
6.5	Results	152

6.6	Summary	165
7	Discussion and future work	169
7.1	Discussion	169
7.2	Future work	175
8	Conclusions	179
	References	184
A	Appendix to Chapter 4	202
A.1	Data appendix	202
A.2	Estimation of transit time	209
A.3	Additional figures	211
B	Appendix to Chapter 5	213
B.1	Mathematical appendix	213
B.2	Data appendix	217
B.3	Additional results	221
C	Appendix to Chapter 6	224
C.1	Mathematical appendix	224
C.2	Data appendix	229
C.3	Additional results and figures	231
D	Correspondence tables	236
D.1	Aggregation of extra-EU data into industries	236
D.2	Aggregation of OECD-MTC data into industries	239

List of Figures

4.1	Kernel estimates of density of the seaborne, airborne and total iceberg transport cost measures	78
4.2	The importance of time costs in trade	78
4.3	Kernel estimates of density from relative time cost distributions	78
5.1	Tourism and prices	107
5.2	Tourism and geography	107
5.3	Parameter estimates of the variance-covariance matrix of the tourism dataset	120
6.1	Illustration of net price increases in trade and tourism as a result of a carbon emissions pricing scheme in international transport.	152
6.2	Average supply prices in trade	155
6.3	Average transport costs in trade	155
6.4	Trade related changes in real income	155
6.5	Average supply prices in tourism	156
6.6	Average transport costs in tourism	156
6.7	Tourism related changes in real income	156
7.1	Historic versus future changes in fuel price indexes	172
7.2	Structure of an IAM consisting of the trade, tourism and transport sectors.	176
A.1	Number of observations by mode of transport.	204

A.2	Cumulative tonnage breakdown by mode of transport	204
A.3	Air speed as a function of average trip distance.	210
A.4	Sea speed as a function of average trip distance.	211
A.5	Growth in airborne vs. seaborne trade	211
A.6	Differences in calculated welfare changes of policy A using options 1 and 2.	212
A.7	Differences in calculated welfare changes of policy B using options 1 and 2.	212
A.8	Sea vs. air distance of manufactured goods imported into the EU	212
C.1	Approximated rate of CO ₂ reduction in international transport	230
C.2	Dynamic price changes in trade	231
C.3	Dynamic price changes in tourism	231
C.4	Reductions in real income by country due to a carbon price of \$300/tCO ₂ in international sea transport	232
C.5	Reductions in real income by country due to a carbon price of \$300/tCO ₂ in international air transport	232
C.6	Reductions in real income by country due to a carbon price of \$300/tCO ₂ in international air and sea transport	232
C.7	Reductions in real income of trade against tourism due to a carbon price of \$300/tCO ₂ in international air and sea transport	233
C.8	Changes in income vs. changes in the price index in the industry sector	233
C.9	Changes in income vs. changes in the price index in the tourism sector	233

List of Tables

1.1	International transport CO ₂ emissions by transport activity in 2013.	17
4.1	Approximation of transport costs.	64
4.2	The value of time in international trade	71
4.3	Welfare impacts associated with slow steaming and substituting nearly all air with ocean freight	86
5.1	Tourism and prices.	110
5.2	Travel costs and tourism prices.	112
5.3	Global tourism patterns.	116
5.4	Tourism competitiveness.	121
5.5	Gains from international tourism.	127
6.1	Overview of data and input parameters of the realised CGE model	145
6.2	Validation of the realised international maritime and air transport system .	158
6.3	International trade and tourism in a CO ₂ -constrained world	160
6.4	Tests for discrimination against economically disadvantaged countries	164
A.1	Descriptive statistics by industry and transport mode of extra-EU imports .	207
A.2	Descriptive statistics of unit and ad valorem transport costs by industry in seaborne trade	208

B.1	Top ten destination countries by international tourist arrivals	218
B.2	Unit and ad valorem air travel costs in international tourism	218
B.3	Gains from international tourism (full list).	221
C.1	Sensitivity analysis of results in Table 6.3 using lower demand elasticities . .	234
C.2	Sensitivity analysis of results in Table 6.3 using higher demand elasticities .	235

Nomenclature

Acronyms

AP	Air Premium
ASC	Alternative specific constant
BOP	Balance of Payments
CC	Carbon cost
CDF	Cumulative Distribution Function
CDM	Clean Development Mechanism
CER	Certified Emission Reductions
CES	Constant Elasticity of Substitution
CGE	Computational General Equilibrium
CIF	Cost, Insurance, Freight
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRS	Constant Returns to Scale
EEDI	Energy Efficiency Design Index
ETS	Emissions Trading Scheme
FGLS	Feasible Generalized Least Squares
FOB	Free On Board
GATT	General Agreement on Tariffs and Trade
GMM	Generalized Method of Moments
GPML	Gamma PML
GWP	Gross World Product
IAM	Integrated Assessment Models
ICAO	International Civil Aviation Organization
ICS	International Chamber of Shipping
IEA	International Energy Agency
IIA	Independence of Irrelevant Alternatives
IMF	International Monetary Fund
IMO	International Maritime Organization
INDC	Intended Nationally Determined Contribution

IRS	Increasing Returns to Scale
ITF	International Transport Forum
LLDC	Landlocked Developing Country
MAC	Marginal Abatement Cost
MBM	Market-Based Measure
MNL	Multinomial Logit
MTC	Maritime Transport Cost
OEM	Original Equipment Manufacturer
OLS	Ordinary Least Squares
PML	Pseudo Maximum Likelihood
PPML	Poisson PML
RPK	Revenue Passenger-Kilometres
RTK	Revenue Tonne-Kilometre
SCC	Social Cost of Carbon
SIDS	Small Island Developing States
TFP	Total Factor Productivity
TTCI	Travel and Tourism Competitiveness Index
UNFCCC	United Nations Framework Convention on Climate Change
UNWTO	World Tourism Organization
WTO	World Trade Organization
WTTC	World Travel and Tourism Council
WITS	World Integrated Trade Solution

Notation

Scalars	Uppercase or lowercase characters
Vectors	Bold lowercase characters
Matrices	Bold uppercase characters

Symbols

a	Preference parameter
d	Deficit (trade or tourism) [\$/capita]
f	Fixed costs (trade) [\$]; Airfare (tourism) [\$/tourist]
g	Group index
h	Sector index
i	Country index

j	Country index
k	Location (tourism) $\neq l$
l	Transport mode (trade) $\neq m$; Location (tourism) $\neq k$
m	Transport mode $\neq l$
p	Price [\$/unit]
q	Quantity [unit]
s	Time costs (trade) [\$/unit], activity (tourism) [1]
t	Transport costs [\$/unit], Time index [year]
u	Utility
v	Variable indicator
\mathbf{v}	Vector of variables v
w	Wage [\$/worker]
x	Choice attribute
y	Transport output [t.km, p.km]
z	Productivity [unit/worker]
A	Preference parameter
AP	Air premium [\$/unit]
C	Costs [\$]
\mathcal{C}	Choice Set
D	Distance, Deficit (trade or tourism) [\$]
E	Index for the economy as a whole i.e. the combined total of all sectors
\mathbb{E}	Expected value
F	CDF of the Frechet distribution
G	Number of groups g [1]
H	Number of sectors $h = 1, \dots, H$ [1]
H_0	Null hypothesis
I	Number of countries $i = 1, \dots, I$; Inbound tourism effect [-], Industry sector (index)
L	Labour [Nr. of workers] [1]
M	Number of transport modes m [1]
MC	Marginal costs [\$/unit]
N	Number of firms (trade) [1]; Number of tourists (tourism) [1]
O	Outbound tourism effect
P	Price index [-]
\mathbb{P}	Probability [-]
Q	Quantity in tonnes [t]
S	Number of activities s (tourism) [1]
T	Tourism sector (index)
TT	Transit time in [h]
U	Utility [-]
V	Systematic utility [-]

VOT	Value of time [\$/unit/time]
W	Real income (welfare) [\$]
X	Expenditure [\$]
Y	Production output [\$]
α	Expenditure share [-]
β	Coefficient estimate
γ	Output elasticity [-]
δ	Fixed effect
ϵ	Price elasticity of demand [-]
ε	Error term
ζ	Cost function
η	Emissions factor (fuel related or output related) [gCO ₂ /unit]
θ	Shape parameter of the CDF, inverse measure of heterogeneity
ϑ	Transport output related quality differential [-]
κ	Orthogonal error term, return trip factor [-]
λ	Expenditure share (budget share) [-]
μ	Scale parameter of the Gumbel distribution [-]
ξ	Index of pure technical change [-]
π	Expenditure share (budget share) [-]
ρ	Elasticity other than σ or ϵ [-]
σ	Elasticity of substitution [-]
ς	Heteroskedastic error term
τ	Ad valorem (iceberg) transport or travel cost [-]
ϕ	Percent reductions in CO ₂ of the transport industry [-]
χ	CO ₂ tax equivalent of net fuel prices [-]
ψ	Idiosyncratic preference parameter [-]
ω	Index of variety
Γ	Gamma function
Δ	Difference
Φ	Price parameter (tourism) [-]
Ω	Number of varieties ω [1]

Chapter 1

Introduction

Economic activity is intertwined via international trade and tourism. This interdependence results from having access to goods and services at lower cost from foreign countries. In economic terms, trade and tourism globalisation is therefore beneficial. At the same time however, international trade and tourism impact the environment through transport energy use and emissions. Studies related to environmental policy analysis in international transport consist of environmental impact assessments at the local and global level, optimisation and operational research studies (fuel optimisation, route optimisation, integrated assessment models), technology and innovation research studies (use and production of biofuels, electrification), studies related to supply responses (technology uptakes, marginal abatement cost curves, game theory), as well as studies related to the demand responses (welfare impacts, mode choice behaviour).

This thesis focuses on the demand responses. It evaluates the demand implications of environmental transport policies in international trade and tourism. It starts by laying out a theoretical framework for international trade and tourism, continues by collecting data and estimating key structural model parameters thereof, and ends by calculating the changes in consumer prices and income within a general equilibrium condition in the industry and tourism sectors in each country. It then uses these results to investigate patterns of discrimination (if any) against countries with a high dependency on either international trade or tourism and their level of development (developing vs. developed countries) if international transport would be subject to an environmental tax. Results of this thesis therefore provide insight into environmental policy regulation and development at the intergovernmental level.

1.1 Context

National economies are linked through trade and tourism. In 2015, the dollar value of world merchandise exports reached 17 trillion, a quarter of world economic output (WTO, 2013). In the same year, the tourism sector comprised 1.2 billion travellers who spent US\$ 1.26 trillion in foreign countries, corresponding to a 7% share of the world's exports in goods and services or a tenth of world economic output (UNWTO, 2016).

Both the aviation and maritime transport industries are prime facilitators of global trade and tourism. Air and sea transport are dependent on fossil fuels, which, when burned, form CO₂. Trade and tourism therefore impact the environment through transport emissions. In 2013, the international aviation and maritime industry released 1,100 million tonnes of CO₂ (MtCO₂), representing a 4.7% share of global energy related CO₂ (IEA, 2015). Slightly more than half of these emissions is related to the import and export of manufacturing goods and natural resources. The remainder of the emissions is related to the inbound and outbound travel of passengers. Table 1.1 gives an overview.

Despite significant technological progress—particularly in the aviation industry (see e.g. Schäfer et al., 2009)—emissions from both industries have been growing rapidly over the last couple of years and are thus of increasing concern. Given the increasing importance of international trade and tourism in a globalised world, international transport emissions are likely to further increase in the future, with projected growth rates of around 2.4% per year¹.

Table 1.1: International transport CO₂ emissions by transport activity in 2013.

(1) Activity	(2) Trade [MtCO ₂]	(3) Tourism [MtCO ₂]	(4) Total [MtCO ₂]
International transport	645	455	1,099
International sea transport	581	28	609
Non-manufacturing trade	265	0	265
<i>Bulk</i>	131	0	131
<i>Oil</i>	98	0	98
<i>Gas</i>	36	0	36
Manufacturing trade	316	0	316
<i>Containerized</i>	161	0	161
<i>Other</i>	155	0	155
Passenger	0	28	28
International air transport	63	427	490
Passenger (incl. belly freight)	27	427	454
Manufacturing trade (dedicated freighter)	37	0	37

Notes: Numbers refer to million metric tons of CO₂. Source: IEA (2015) with a year 2012 %-split by ship type from IMO (2014) and a year 2013 %-split between dedicated air freight carriers and freight transported in passenger aircraft (belly freight) from Boeing (2014). The split between air passenger and air cargo transport emissions is approximated by comparing global RPK and converted RTK 2013 values.

¹Calculated as the compound annual growth rate between 1990-2013 using numbers from the IEA (2015).

De-carbonising the international transport system however remains a challenge. In comparison to most other industrial sectors, both international transport industries have only a relatively limited number of mitigation options available², next to low fleet turnover rates, which cause a comparatively long delay in implementing these options.

Given the anticipated emission growth rates on the one hand, and the limited number of mitigation options available at a significant higher cost on the other, a substantial de-carbonisation of both industries in the long term can thus only be achieved through regulatory or market-based measures (MBMs). MBMs provide alternatives to reduce emissions through levies, trading of allowances, or offsets. Given this flexibility, MBMs are often preferred over regulatory measures and the international transport industry is no exception (ICAO, 2016, IMO, 2016).

Once confronted with an MBM, transport firms in both the international aviation and maritime industry will strive to absorb as little as possible of the associated cost increases and therefore pass them down the supply chain to consumers in the form of price increases. MBMs in international transport will therefore inevitably impact the industry and tourism sector in each country through higher consumer prices, and thus affect the volume, direction, and composition of international trade and tourism. At the same time, countries with a higher dependency on international trade and tourism will be affected to a greater extent than those relying more on domestic markets. The questions to what extent carbon emissions pricing schemes in international transport cause global economic impacts and disproportionate economic welfare losses have been debated at intergovernmental organisations for years and have now become one of the most pressing barriers to practical implementation (UNFCCC, 2012, ICAO, 2016, IMO, 2016).

1.2 Problem statement

MBMs are the preferred mechanism to ensure a significant de-carbonisation of the international transport industries over a relatively shorter period of time (see section above). Concerns over these policy measures however exist with respect to causing disproportionate economic impacts and discrimination against countries with a higher dependency on international trade and tourism (ICS, 2017, ICAO, 2016).

To date, there is limited research that examines the role of international transport in the industry and tourism sectors in each country and how these sectors are affected by exogenous price shocks through international transport. Although transport research focuses

²Technologies enhancements in international aviation and maritime transport must not significantly compromise payload and range capabilities e.g. due to excess weight. Other sectors are able to utilise carbon capture and storage technologies, heat recuperation with large heat exchangers, alternative energy storage systems such as batteries in road transport or reduce emissions at the tailpipe with large-scale filters.

on many crucial aspects influencing demand (e.g. the analysis of travel behaviour), the link to consumer theory and the underlying theoretical frameworks is often omitted (e.g. Martinez, Kauppila and Gachassin, 2014; Gallagher and Taylor, 2003; Keen, Parry and Strand, 2013; Ben-Akiva and De Jong, 2013; Keum, 2008; Balli, Balli and Louis, 2016). Limitations therefore exist with respect to the combined treatment of consumer demand and transport supply and the combined analysis of the trade and tourism sectors for four main reasons.

First, the link between consumer demand and transport supply is rarely accomplished in the literature. Transport is vital to make goods and services accessible to consumers. The demand for transport is therefore a direct result of the consumers demand for goods and services. Yet, it is common practice in the literature to treat consumer demand and transport supply independently of one another. Models of consumer demand usually account for some form of transport costs, but do not specify in detail what these costs entail (Krugman, 1980; Eaton and Kortum, 2002; Melitz, 2003). This makes the impacts of exogenous fuel price shocks on consumer prices difficult to quantify. For example, the costs of a transport firm include labour, material, capital, and fuel costs (to name but a few). Without the link between consumer demand and transport supply, the level of cost increases from individual cost elements (e.g. fuel costs) passed down the supply chain to consumers in the form of price increases cannot be determined. The difficulties that arise from an independent treatment of consumer demand and transport supply can also be identified in models of international transport systems. Although they are often rich in detail, changes to transport demand are usually treated as exogenous (OECD ITF, 2015; Reynolds et al., 2007; Smith et al., 2011) by using e.g. off-line results of future projections of trade between countries. In this case too, exogenous fuel price shocks cannot be linked to changes in consumer prices and hence consumer demand.

Second, if the link between consumer demand and transport supply is accomplished, shortcomings in the model specification exist. One of the key economic tools to link consumer demand with transport supply is the gravity model. Gravity equations in international trade link bilateral trade demand (imports) to relative price differences across countries and multilateral resistance terms (price indexes). Given the log-linear nature of the gravity equation, the independent variables need to be specified in multiplicative form. The cost component related to transport therefore needs to be transformed into the one plus the ad valorem tax equivalent to the production costs, so as to be compliant with the theoretical framework of consumer demand (gravity). In many research projects related to transport demand, this transformation is rarely accomplished (e.g. The Economist Intelligence Unit, 2008; Vivid Economics, 2010; Cristea et al., 2013).

Third, no theoretical framework exists for international tourism flows. In contrast to the well established literature on trade theory and theoretical models of trade (Krugman, 1980; Eaton and Kortum, 2002; Melitz, 2003), no theoretical framework exists that links

international tourism spending to a country's economic output and thus welfare. Most of the research related to tourism is concerned with economic and ecological impact analyses on a country level and the sustainable development of tourism (e.g. Mathieson, Wall et al., 1982; Archer, Cooper and Ruhanen, 2005; Sharpley, 2000; Ceballos-Lascuráin et al., 1996). In the absence of dedicated theoretical frameworks, the gains from international tourism across countries have therefore never been investigated before. Linked to this uncertainty are the welfare impacts associated with exogenous price shocks on international transport (aviation in particular), which can therefore not be quantified.

Fourth, the combined economic analysis of the industry, tourism, and transport sectors has never been accomplished before. Table 1.1 illustrates that the international air and maritime transport industries are intrinsically interlinked through trade. If all aircraft are operated under an MBM, the tourism sector will be affected through passenger transport and the industry sector through the transport of freight in international trade. Once an MBM is enacted in either the aviation and maritime transport industry, it is likely that the other sector will follow and introduce an MBM as a result of increased societal and political pressure. A combined treatment thus becomes important to holistically understand the economic impacts at the country level, as some countries are more dependent on international tourism receipts or industrial export revenues than others.

Given the multitude of issues and challenges involved in establishing the link between consumer demand and transport supply in the trade and tourism sectors and although the policy debate on environmental regulation in international transport is perennial, the question to what extent the industry and tourism sectors are subject to economic impacts as a result of a carbon emissions pricing scheme in international transport has not been investigated thoroughly in the literature.

1.3 Aim and Scope

The aim of this thesis is to quantify the country-level economic impacts that result from a carbon price in international transport. To achieve this objective, this thesis (i) develops a theoretical framework of consumer demand for international trade and tourism, (ii) collects and estimates missing data on prices, transport costs, and gross output in each sector, (iii) estimates macro-level predictors of global trade and tourism flows, (iv) builds a general-equilibrium model using the theoretical frameworks of consumer demand and the estimated parameters, and (v) quantifies changes in real income in each sector and country (for which data can be obtained).

The models include both the demand and supply side. On the demand side, trade and tourism are described using gravity equations. On the supply side, the costs associated

with the international transport of goods and services are described using a cost function of a representative transport firm. The two models are balanced via transport prices. With knowledge of the price elasticity of demand, changes in transport costs can be linked to changes in prices and hence changes in demand. On a country level, these results provide insight into the magnitude of welfare impacts in each sector that are to be expected if international transport is subject to a market-based CO₂ reduction policy. On a global level, the calculated economic impacts across countries provide insight into patterns of discrimination against countries with a higher dependency on international trade and tourism.

Limits to this research mainly arise from the modelling framework. As general equilibrium models are not capable of determining price levels uniquely, the obtained results are calculated relative to a chosen reference or constant (the numeraire). The general equilibrium model iterates over the changes in income and consumption in each sector and country. In this way, the calculated changes reflect general equilibrium changes on the demand side in the trade and tourism sectors. The iteration over (reduced) consumer demand and (hence reduced) transport supply (impacting transport prices) is not accomplished in this thesis as a result of the significant increase in modelling complexity (see Section 7.2).

This study does also not account for any transition dynamics in moving the global economy from an environmentally unconstrained to an environmentally constrained international transport system. This includes the dynamics of technology uptakes and operational efficiency improvements on the supply side as well as firm entry and exit and changes in labour supply on the demand side. On the supply side, technology uptakes and improvements in operational efficiency are assumed to scale approximately linearly with increases in fuel costs. On the demand side, since carbon emissions pricing schemes mainly affect marginal costs, the changes in fixed costs and firm entry and exit are assumed to be insignificant and are therefore ignored.

Due to data limitations, this thesis does also not take into account spillover effects, individual price adjustments by transport firms on strategically important trade and tourism routes (network effects), the embodied carbon in goods imports (see e.g. Figure 3 in Grubb et al., 2015) and any form of carbon leakage. Not incorporating these effects (including the transition dynamics mentioned above) allows to investigate the welfare implications in isolation, which is pedagogically useful, considering the complexity involved in the interaction of global flows in terms of income and spending in each sector and country.

1.4 Significance of the study

This thesis makes contributions on a theoretical, empirical, and policy level. On a theoretical level, one intended outcome of the study is to develop a theoretical framework

of international trade by mode of transport and a theoretical framework of international tourism. Both theoretical frameworks could influence future research in the economics discipline, and in particular in the macroeconomics discipline related to tourism. As no theoretical framework exists to explain international tourism flows, the model developed in this thesis could be useful for other researchers, as it can be extended in many possible ways to account for additional micro and macro-level predictors of tourism.

A second intended outcome of the study is to develop and provide a general equilibrium model of the industry, tourism and international transport sectors that could be used for further research to e.g. study specific policy designs. The model could also be extended by linking the trade model and tourism model with partial equilibrium models of the air and marine transport system (see future work in Chapter 7) to arrive at an integrated assessment model in which mode shifts and technology uptakes are treated endogenously.

On an empirical level, a third intended outcome of the study is to estimate the value of time in international trade and to estimate the price elasticity of demand in international tourism. Many transport related studies use parameter estimates of the value of time to transfer transport costs into generalised costs. Estimates of the price elasticities of demand are also frequently used either as an input to other studies (e.g. to calculate the welfare impacts) or as a benchmark for comparison.

A fourth intended outcome of the study is to establish a dataset (including estimates in case of missing data) of domestic income and expenditure and international income and expenditure by sector (industry and tourism) and country. This dataset could be used for further research in the macroeconomics and transport economics field as it links and compares a country's international contribution to and dependency on trade and tourism.

On a policy level, a final intended outcome of the study is to quantify the extent of which carbon emission pricing schemes in international transport lead to discrimination against countries with a relatively high dependency on income from international trade and tourism. In particular, this study addresses the concerns of many countries to be discriminated by environmental policy schemes in international air and maritime transport (ICAO, 2016, ICS, 2017). It provides insight into the extent of which discrimination may be expected (if any) and discusses ways of how these may be overcome in the form of rebate mechanisms. It therefore reduces the uncertainty associated with the demand implications of international policies governing trade and tourism. Results of this study therefore provide insight to policy makers at the intergovernmental level.

1.5 Overview of the study

This thesis consists of seven further chapters. The following Chapter 2 provides a review of the literature in four main parts, including a review of the economics literature on (1) trade and (2) tourism, (3) a review of the literature on international transport and the environment, and (4) a review of the legal policy framework of international transport policies.

Chapter 3 describes the methodology employed in this study. The point of departure for the described analysis are theory-consistent, multi-country gravity models of international trade and tourism. These models are then used in counterfactual exercises to investigate the economic impacts of exogenous price shocks.

Chapter 4 focuses on column 2, Chapter 5 on column 3 of Table 1.1.

Chapter 4 develops a theoretical framework of consumer demand to explain international trade flows by mode of transport. The model features on the supply side a component of transport and time costs that firms minimise with respect to choosing an optimum transport mode for exporting. The value of time in international trade is estimated using trade data by mode of transport from Eurostat. The theoretical framework and parameter estimates are used to explore relative price changes of operational mitigation strategies in ocean freight versus air freight.

Chapter 5 develops—in the absence of dedicated theoretical frameworks—a model of comparative advantage in international tourism. The model describes consumers of having discrete choices over worldwide locations to undertake activities. The resulting system of equations is shown to be observationally equivalent to the standard gravity equation in international trade, implicating a parsimonious way to learn about a country’s competitiveness and economic dependency on international tourism. Data on airfares and the number of tourist arrivals by country are used to estimate the price elasticity of demand in international tourism, which, in combination with the theoretical framework, is used to calculate the gains from international tourism across countries.

Chapter 6 then combines the tourism model and a simplified version of the trade model (without air freight) into a multi-sector, multi-country general equilibrium model. This model is then used to quantify changes in real income in more than 100 countries by imposing a carbon tax in the form of a global bunker fuel levy in the international aviation and maritime industry.

Chapters 7 contains the discussion and Chapter 8 concludes.

Chapter 2

Literature review

This literature review consists of four sections, each of which addresses one of the main topics of this thesis as follows. The first section provides a review of the economics literature on trade theory, with a focus on models of trade by mode of transport. Section 2.2 provides a review of the economics literature related to tourism. Section 2.3 provides a review of the economics and transport literature related to international transport and the environment and the policy cases investigated. The last section provides a review of the legal policy framework of international transport policies.

2.1 Trade

The section on trade gives a brief overview of the macroeconomics literature related to trade theory, the gravity equation, the gains from trade, and the role of transport in trade.

Trade Theory. Three substantial contributions shaped the evolution of trade theory. In chronological order, these are: Ricardo’s theory of comparative advantage, Krugman’s theory of economic geography, and the theoretical literature on firm heterogeneity and trade.

One of the most celebrated insights in the theory of international trade is Ricardo’s conceptual framework of absolute and comparative advantage. Because countries have differential access to technology, their productivity varies across goods and countries. As formalised in Eaton and Kortum (2002), a country’s state of technology reflects its absolute advantage in producing some varieties of the goods at a lower cost, relative to other varieties of goods, compared to another country¹. Ricardo’s *theory of comparative advantage* therefore

¹A number of numerical examples can be associated with the concept of comparative advantage. For example, if z denotes the labour required per unit of output of products A and B, country j has an *absolute* advantage in product A if $z_j^A < z_i^A$, and a *comparative* advantage in product A if $z_j^A / z_j^B < z_i^A / z_i^B$

predicts that countries should specialise in producing and exporting commodities in which they are relatively more productive.

Comparative advantage among countries may however arise for several reasons. Heckscher (1919) and Ohlin (1935) identified the role of differences in factor endowments as a determinant of comparative advantage. In this case, countries are assumed to have identical states of technology but different factor endowments. The *Heckscher-Ohlin theorem* states that a country is led to specialise in the production of goods that use its relatively abundant factor more intensively. Exporting such goods leads to a rise in the real and relative return to its relatively abundant factor (Panagariya, 2009). A country is therefore led to import products that demand its relatively scarce factor more intensively. Because of these features, the Heckscher-Ohlin model is often applied in the form of a two-factor (labour and capital), two-good, and two-country model, as e.g. formalised by Samuelson (1948). It is therefore not ideally suited to the research aim and scope of this thesis.

Monopolistic competition among firms with economies of scale on the one hand, and the presence of trade costs on the other (often referred to as economic geography), affects trade through an additional channel, which Krugman (1980) identified as home-market effect. In a frictionless world without trade costs, firms can sell to all countries at equal cost. In the presence of trade costs however, firms in countries with larger domestic markets of a particular good specialise in the production of these goods relative to countries with smaller markets (Helpman, 2011). In this way, firms can cheaply supply the larger market and its costs associated with supplying the smaller, more expensive market remain relatively low, so as to realise economies of scale. Firms may therefore locate near a market with higher production costs (higher labour costs) but better access to markets (less trade costs) (Krugman, 1991, p. 96). As a result, a disproportionately higher number of firms will locate in the larger market and locations of larger markets will be supplying goods to other markets and therefore become net-exporting markets. The location of production in space is referred to as 'economic geography'.

Krugman shows in his 1980 paper that international trade is related to patterns in which one location emerges as the manufacturing core, while the other becomes an agricultural periphery (referred to as core-periphery equilibrium) due to large economies of scale, low transport costs and a large share of manufacturing in expenditure (Krugman, 1991, p. 113). A higher share of manufacturing in expenditure makes a core-periphery pattern due to stronger forward and backward linkages more likely, while an increase in the price elasticity of demand for any particular good lowers the importance of economies of scale and makes a core-periphery pattern more difficult to sustain. These two economic forces may outweigh comparative advantage in a frictionless world without trade costs. In other words, "trade need not be a result of international differences in technology or factor

(Maneschi, 2009). The product with a relatively lower cost of production is exported in exchange for the other.

endowments" (Krugman, 1979). A number of studies followed to identify home market effects (e.g. Helpman, 1987; Head and Ries, 2001; Hanson and Xiang, 2004).

Krugman's alternative theory to explain trade is referred to as *New Trade Theory*. Trade models where productivity does not vary across firms within a country are also referred to as *Homogeneous Firm Models* to distinguish them from *Heterogeneous Firm Models*, which are described next.

In the monopolistic competition model of trade with homogeneous firms, it is profit maximising for firms to (costlessly) leave one set and produce another, unique set of product varieties. Countries are therefore completely specialised in different product varieties and utilise *intraindustry trade* (Feenstra, 2003b). As shown by Melitz (2003) however, trade liberalization leads to within-industry reallocations of resources across firms, as evidenced by micro-level data on plants and firms (Bernard, Jensen and Lawrence, 1995; Bernard and Jensen, 1999). This raises average industry productivity as low-productivity firms exit and high-productivity firms expand to enter export markets (Melitz and Redding, 2015). Trade liberalisation therefore also raises firm productivity. And theories of firm heterogeneity and trade (Melitz, 2003; Yeaple, 2003; Bernard et al., 2003) provide a better understanding of mechanisms through which an economy responds to trade through entry and exit of firms, and the expansion of and higher productivity of exporting firms. Trade models where productivity varies across countries and across firms within a country are referred to as *Heterogeneous Firm Models*. The collection of models which focus on firm heterogeneity and trade, as formalised by Melitz (2003), are sometimes also referred to as '*New*' *New Trade Theory*, to be able to distinguish them from the collection of models related to *New Trade Theory*.

There has been a rapid uptake of the Melitz (2003) model of firm-level heterogeneity and product differentiation with monopolistic competition in the literature. Among the many applications of this model, three studies are mentioned with respect to their model extensions. Antràs and Helpman (2004) let heterogeneous firms choose different ownership structures and supplier locations. Bernard, Redding and Schott (2007) include reallocations of resources both within and across industries and countries, and the resulting job turnover in all sectors. Bernard, Redding and Schott (2011) develop a multiple-product, multiple-destination model of firms, which allows for heterogeneity in ability across firms and in product attributes within firms.

Gravity. The gravity equation in international trade evolved in three significant steps. The initial empirical finding of relating trade with country size and distance, the step in moving from naive gravity to structural gravity (including the usage of fixed effects for estimation), and the link of trade theory with the gravity equation, which today, provides a consistent framework of economic theory and empirical evidence to study the determinants of trade.

The gravity equation is a linear in logs equation and states, in its most simplistic form that bilateral trade is directly proportional to the product of the countries' GDPs and inversely proportional to the distance between the two countries (hence the analogy to Newton's law of universal gravitation and the name *gravity* equation). The relationship between the country GDP's and distance was first shown in an empirical study by Tinbergen (1962). Armington (1969) added to this finding an extremely simplified but useful theoretical foundation: Each country produces a different good, and consumers in each country would like to consume at least some of each country's goods. A utility function that mimics such a consumer behaviour is the constant elasticity of substitution (CES) function. Under CES, preferences are homothetic. The CES demand function is therefore commonly used in the trade literature. Due to its simplified structure yet robust prediction, the Armington model (as formulated by Anderson, 1979) is often used as starting point in international trade theory before moving to more complex models such as the heterogeneous firms model.

The next significant step in the evolution of the gravity equation involved the movement from *naive* to *structural* gravity. McCallum (1995) stimulated a large amount of research to understand border effects in his comparison of Canadian intra-national and U.S.-Canadian international trade. Treffer (1995) pointed to trade that is 'missing' relative to the Heckscher-Ohlin-Vanek theorem that he invoked 'home bias' consumption. Leamer and Levinsohn (1995) suggested to include the effect of distance into economic thinking. And Krugman (1995) intuitively pointed to the effect of a country's remoteness, which cannot be explained by using bilateral distance alone. These remoteness indexes have now become multilateral resistance terms that Anderson (1979) originated and Anderson and Wincoop (2003) popularized.

The presence and consideration of multilateral resistance terms in the gravity equation distinguishes structural gravity from naive gravity. The multilateral resistance terms—which are now an essential part of every theoretical trade model—represent price indexes across goods consumed from different countries. The prices paid by consumers are inclusive of trade costs. Anderson and Wincoop (2003) showed that the multilateral resistance terms change if trade costs change. Estimating the role of trade barriers in international trade without accounting for the multilateral resistance terms therefore causes biased estimates. Papers that appeared before Anderson and Wincoop (2003) can therefore be universally characterised into papers that omitted the multilateral resistance terms (Baldwin and Taglioni, 2007).

The last step in the evolution of the gravity equation was its joint consideration with theoretical models of trade. Although gravity always played an influential role in trade theory as in Armington (1969), it was Anderson and Wincoop (2003) and Eaton and Kortum (2002) who laid down the theoretical foundation for the gravity equation. As Head and Mayer (2014) note, both models build on micro-theoretical foundations and point toward estimation methods that take into account the underlying structure of these models.

While the implicit solution of the gravity equation to take into account the multilateral resistance terms as suggested by Anderson and Wincoop (2003) was difficult to implement, Eaton and Kortum (2002) already pointed towards a much more convenient solution in using dummy variables by origin country to take them into account. The estimation of gravity equations using importer and exporter fixed effects for each country to capture the multilateral resistance terms—as is standard today—was then finally demonstrated by Feenstra (2003b) and Redding and Venables (2004). Estimating gravity equations has thus become a relatively easy task and led to a rapid uptake in usage in empirical work.

The Ricardian trade model as formalised by Eaton and Kortum (2002) deserves particular mention. Not only did it point to estimating the gravity equation using fixed effects, but it also demonstrated that a gravity equation can be obtained from a multinomial logit model of discrete choice. This was surprising as Eaton and Kortum (2002) depart from the standard CES approach that somewhat manifested in the way how trade models were built from theory. Their theoretical approach towards developing this model therefore turned out to be extremely elegant and has been receiving increasing attention. Chapter 5 makes use of this conceptual framework and develops a theoretical model of international tourism flows.

The last missing link of the gravity equation with trade theory was then only in terms of the heterogeneous firm model. As demonstrated by Chaney (2008) and Helpman, Melitz and Rubinstein (2008), the determination of bilateral trade flows in the heterogeneous firm model requires the distinction between intensive and extensive margins of adjustment to trade shocks. Chaney (2008) showed that the price elasticity of demand becomes dependent on the degree of firm heterogeneity in the presence of fixed trade costs, which can then be subdivided into an intensive and extensive margin elasticity. Helpman, Melitz and Rubinstein (2008) and Melitz and Ottaviano (2008) demonstrated how to estimate this model. Their formulation differs from a homogeneous firm model by additionally controlling for the fraction of firms participating in trade, which can also take the value of zero in the presence of high fixed costs and therefore account for zero trade flows in the estimation of the gravity equation.

In sum, the evolution of the gravity model was driven by the development of trade theory, empirical evidence, and estimation methods and is likely to continue to do so. Given that gravity is underlying in a wide range of trade models, the gravity equation has become the workhorse model of international trade. Head and Mayer (2014) show how the main variants of trade models can be grouped into supply-side and demand-side models. Ultimately, they show that whether heterogeneity of goods (homogeneous firm model), heterogeneity of productivity of firms (heterogeneous firm model), or heterogeneity of countries (Ricardian trade model) is used to in theoretical models to explain bilateral trade flows – they all yield into gravity.

Gains from trade. Important contributions have also been made to quantify the welfare gains from trade. Eaton and Kortum (2002) first computed changes in real income as a function of the domestic consumption share and the price elasticity of demand in the Ricardian trade model. Arkolakis et al. (2008) calculated the gains from trade from the Melitz (2003) model of heterogeneous firms with fixed exporting costs. Arkolakis, Costinot and Rodríguez-Clare (2012) then generalised these results. They show that the welfare predictions from trade remain identical for the Armington trade model, the Ricardian trade model, and the homogeneous and heterogeneous firms models as they can be computed using only two statistics: the domestic trade share and the price elasticity of demand (the trade elasticity). Within that class of models, they argue that new margins of adjustment to foreign trade shocks (in terms of consumption or labour reallocation) cannot change the total size of the gains from trade. In a more recent study however, Melitz and Redding (2015) show that, relative to homogeneous firm models, endogenous firm selection provides a new welfare margin for heterogeneous firm models of trade. Their result builds on the observation that the domestic trade share and the endogenous trade elasticity are no longer sufficient statistics of welfare in a more general setting with less parameter restrictions. This is because the assumption of a single constant trade elasticity is highly sensitive to small departures from the additional restrictions on the parameter space in Arkolakis, Costinot and Rodríguez-Clare (2012). Relative to the homogeneous firm model, Melitz and Redding (2015) find that there are larger welfare gains from reductions in trade costs and smaller welfare losses from increases in trade costs in the heterogeneous firm model.

Using the framework as in Arkolakis, Costinot and Rodríguez-Clare (2012), Costinot and Rodríguez-Clare (2014) calculate the gains from trade to be 4% on average in a one-sector Armington model. However, accounting for additional economic channels such as multiple sectors and tradable intermediate goods increase the gains from trade significantly as a result of scale effects. More recent research suggests that the gains from trade could be even higher if the dynamic gains from trade are accounted for. Sampson (2016) shows that knowledge spillovers from incumbent firms to entrants is a new source of the gains from trade in the Melitz (2003) model of heterogeneous firms with dynamic selection. In contrast, the study of Pierce and Schott (2016) indicates that there are potentially missing links in the welfare formula developed by Arkolakis, Costinot and Rodríguez-Clare (2012). They find that 21 percent of the decline of manufacturing employment by 5 million jobs since 2000 in the US is attributable to the rising import competition from China (Pierce and Schott, 2016). The loss of local jobs due to trade liberalisation is not taken into account in the quantification of the gains from trade. It therefore remains debatable whether or not such losses outweigh the gains from trade.

In this thesis, the gains from trade and tourism are calculated by taking into account the welfare gains of consuming goods and services at lower prices from foreign countries (this is the standard welfare formula as in Arkolakis, Costinot and Rodríguez-Clare, 2012) as

well as the welfare gains (or losses) of an increase (or reduction) in domestic income (see Sections 5.6 and 6.2). Changes in real income are then calculated from the changes in the price index and the changes in wages, using labour as the numeraire. This approach ensures that the changes in income are taken into account next to the changes in consumer prices. In tourism, the changes in income are quantitatively important as many countries are primarily dependent on international tourism receipts.

Trade and transport. Transport always played an important role in theoretical and empirical research related to trade for two reasons. First, transport costs are one type of trade costs that inhibit trade. Second, data on transport costs can be used to measure the price elasticity of demand.

The comparison of observed trade with predicted frictionless trade provides a measure of trade frictions and their influences such as transport costs and tariffs. Sources of bilateral resistance to trade therefore play an unambiguous role in all international trade theories as a result of the no-arbitrage condition that equates differences in domestic and foreign prices with transport costs and tariffs². Anderson and Wincoop (2003) argue that the ad valorem tax equivalent of trade costs can be as large as 170%, consisting of 21% transport costs (including a 9% tax equivalent of the time value of goods in transit), 44% trade barriers (other than transport costs) and 55% retail and wholesale distribution costs. Given their size, there has been a sustained interest in quantifying the magnitude of barriers to trade.

Data on transport costs (and tariffs) is however difficult to obtain as this type of data is usually not collected by customs authorities. Transport costs are also difficult to quantify as they are comprised of a wide range of cost elements such as shipping, distribution, logistic, and insurance costs. As transport costs are never completely observed, their influence on international trade is often inferred using bilateral distance. After the influential work of Tinbergen (1962), the gravity equation has been used in many studies to show empirically that, after controlling for size (GDP), trade undeniably falls unitarily elastic with distance. Yet, although transport costs are strongly correlated with distance, Head and Mayer (2013) show they only explain between 4 % and 28 % of the distance effect in international trade. This is because of the co-existence of many other trade barriers that can be associated and thus correlated with distance. For example, Allen (2014) estimates information barriers (or search costs) to explain 90 % of the distance effect. In sum, distance will always play a distinct role in international trade as it represents one key variable of the gravity equation. The distance variable is however not informative towards determining the influence of transport costs on trade.

Given the log-linear nature of the gravity equation, transport costs can only be taken into

²Given the no-arbitrage condition, researchers and economic institutions (including the World Bank) also attempted, to measure transport costs from matched partner CIF/FOB ratios, until Hummels and Lugovskyy (2006) however showed that these are error ridden in levels as a result of statistical reporting issues.

account in multiplicative form. First shown by Samuelson (1954), this can be achieved by transferring transport costs into the one plus the tax-equivalent of trade barriers associated with transport costs, also referred to as *iceberg* transport costs³ (see Section 4.5). Since transport costs are now expressed in terms of their ad valorem tax equivalent to prices, the price elasticity of demand can also be measured using data on iceberg transport costs (or tariffs respectively), provided that relevant data can be obtained. The price elasticity of demand in international trade (referred to as the *trade elasticity*) is a structural model parameter of high significance at the macro-level. It measures the proportionate change of imports relative to purchases at home associated with a change in prices (also known as the "Armington elasticity"). In the homogeneous firm model, the trade elasticity is a measure of the degree of homogeneity of products, in the heterogeneous firm model, a measure of homogeneity of the productivity of firms, and in the Ricardian trade model, a measure of homogeneity of countries. Secondly, as shown by Arkolakis et al. (2008), the trade elasticity is—in combination with the domestic trade share—one of the key statistics to quantify the gains from trade.

Feenstra (1994), and applied more broadly by Broda, Greenfield and Weinstein (2006), uses an exact price index for a CES unit-cost function to estimate the trade elasticity using generalized method of moments (GMM) identification via heteroskedasticity. His results indicated a value of 42.9 for silver bullion, 27.2 for gold bullion, 3.59 for steel bars, 8.38 for TV receivers and 6.23 for athletic shoes. Using 1992 trade and tariff data from the US, New Zealand, Argentina, Brazil, Chile, and Paraguay, Hummels (1999) estimates the price elasticity of demand to range from 3 to 8, depending on the type of good (57 considered in total). Limão and Venables (2001) use quotes from shipping firms for a standard container shipped from Baltimore and Maryland in the US to selected destinations and find a value of 3. Eaton and Kortum (2002) and refined by Simonovska and Waugh (2014) use maximum price differences across goods between countries as a measure of transport costs and find a value of 4. Head and Mayer (2014) collect 435 trade elasticity estimates based on either tariffs or transport costs data from 32 papers and obtain a median value of 5, with a standard deviation of 9.3. The high standard deviation is a result of the large range of estimates obtained, as indicated by the aforementioned results. Disaggregating by product group inevitably results into deviations from the central estimate of 5, as some goods may represent nearly perfect substitutes, while others may represent weak substitutes. The price elasticity therefore varies by commodity group as evidenced e.g. in Bas, Mayer and Thoenig (2015) and Shapiro (2016).

The price elasticity of demand not only varies by product group but also by country pair,

³For example, if transport costs represent 10% of the actual price of the good at the factory gate, the iceberg transport costs would take the value 1.1 ($1 + 0.1$). The iceberg measure indicates that 1.1 units of the product must be shipped to the destination country in order for one unit to arrive. According to Samuelson's "iceberg" form specification, the amount $1.1 - 1$ is assumed to "melt" along the way. This is the transport amount paid in units of the exported good.

given that some countries are more dependent on certain types of goods than others⁴. Yet, the gravity equation imposes the structure of treating the trade elasticity as a parameter *common to all countries*.

Given the large number of empirical studies undertaken, this thesis does not estimate the price elasticity of demand in international trade. Rather, for the results in Chapter 6, it uses the central estimate of 5 from Head and Mayer (2014) to quantify the welfare impacts associated with changes in transport prices at an aggregated product level.

In international tourism however, no study exists that estimates the price elasticity of demand using ad valorem transport costs. Chapter 5 therefore not only develops a model for international tourism, but also collects data to estimate the price elasticity of demand in tourism.

Trade by mode of transport. Existing studies that explain bilateral trade flows by mode of transport differ with respect to assuming who or what exhibits mode-specific idiosyncratic behaviour (countries, traders, firms, goods), with respect to measuring deterministic behaviour (transport costs, transit time or a combination of both), and with respect to modelling mode-specific preferences in a general equilibrium trade setting or as an independent model. Harrigan (1995) looks at the volume of trade in manufactured goods by mapping trade in differentiated intermediate goods to the structure of the importing country's industrial sector. His model, featuring CES monopolistic competition, increasing returns, and homothetic preferences, is however rejected by the data. Harrigan (2010) and Lux (2011) model a continuum of goods, where each good is assumed to have an idiosyncratic mode-specific transport cost. Their model is based on Ricardian comparative advantage and builds on the influential work of Eaton and Kortum (2002). Ben-Akiva and De Jong (2013) model logistics decisions at a disaggregated firm level using various logistic cost components before they aggregate over origin-destination flows, which they use for a network assignment model. Given the data requirements, it is unlikely that such a model could be taken to a general equilibrium model of international trade. Hummels and Schaur (2013) let firms choose their preferred mode of transport in comparing the profitability of air versus sea shipping. Allen and Arkolakis (2014) model a continuum of traders using intra-US trade, where each trader is assumed to have idiosyncratic mode-specific transport cost.

The theoretical framework in Chapter 4 builds on the Krugman (1980) model with monopolistic competition and many firms and takes into account marginal costs of production inclusive of transport and time costs. It therefore adds to the specifications listed above a component of time cost which reflects the capital cost of goods locked up in transit.

⁴Feenstra (2003a) and Novy (2013) use instead of the CES-based gravity equation a homothetic translog preference gravity equation to endogenise the trade elasticity. This functional form specification allows the trade elasticity to vary with trade costs. Novy, 2013 concludes that trade cost elasticities appear heterogeneous across import shares.

2.2 Tourism

International tourism did not deserve much attention in the theoretical economics literature, particularly with respect to micro-theoretical foundations that are necessary to determine macro-level predictors of global tourism flows. Most of the literature in international tourism is concerned with economic and ecological impact analyses on a country level and the sustainable development of tourism (e.g. Mathieson, Wall et al., 1982, Archer, Cooper and Ruhanen, 2005, Sharpley, 2000, Ceballos-Lascuráin et al., 1996). Economics research related to tourism often focuses on the determinants of cross-border travel, by examining the benefits derived from buying products at lower prices from foreign countries (Timothy and Butler, 1995; Matteo and Matteo, 1996; Chandra, Head and Tappata, 2014). By large, no attempts have been made to e.g. explain the economic or social phenomenon of global tourism, or the influence of international tourism on the local economy.

Most of the related literature focuses on urban economics. Urban spatial models try to explain key interactions between locations, whether caused due to trade in goods, migration, or commuting. Economic geography models therefore often take into account commuting costs, as they represent a significant share in the consumers' expenditure. For example, Tabuchi and Thisse (2006) consider an economic geography model with mobile firms and workers whose agglomeration within a city generates costs through competition on the housing market. They find that the economy moves from dispersion to agglomeration if commuting costs decrease. Intuitively, economic geography models with commuting costs could therefore also nest agglomeration forces related to tourism.

Ahlfeldt et al. (2015) take this approach further and develop a gravity equation for commuting flows, drawing on the discrete choice framework of Eaton and Kortum (2002) and featuring agglomeration and dispersion forces and an arbitrary number of heterogeneous city blocks. As Head and Mayer (2014) note, with a few minor changes, the model developed by Eaton and Kortum (2002) could also be specified in a way to obtain a gravity equation for tourism.

More recent research by Redding and Rossi-Hansberg (2017) generalises the agglomeration forces as external economies and the dispersion forces as an inelastic supply of land and commuting costs into a quantitative urban model. The model builds on the work of Ahlfeldt et al. (2015) and Lucas and Rossi-Hansberg (2002) and features homogeneous goods in a single traded sector, endogenous amenities, residential and commercial land use, constant returns to scale, endogenous productivity, migration and commuting costs, and idiosyncratic preferences. They show that the model can be used to determine internal city structures and transport infrastructure improvements. Both productivity and amenities are found to strengthen agglomeration externalities by a significant amount.

A few studies also exist with a direct reference to tourism economics. These include, for example, the study by Copeland (1991), who investigates the spillover effect of an expansion of tourism on welfare, output, and factor prices using a general equilibrium trade model. For another example, Faber and Gaubert (2016) study the long-term economic consequences of the services sector due to tourism in Mexico, including spillover effects on manufacturing production. Both these studies link theoretical elements of trade economics with tourism economics and pose interesting scopes of applications.

Chapter 5 takes the approach of linking quantitative urban models with tourism activities further and develops a dedicated theoretical model for international tourism, by applying theoretical elements and concepts of international trade to the economics of international tourism. In contrast to the studies which treat tourism as one additional economic feature of their model (as e.g. in Faber and Gaubert, 2016), the research in Chapter 5 provides a fundamental theoretical explanation for the agglomeration of economic activity in tourism, next to an empirically relevant quantitative model to perform general equilibrium counterfactual policy exercises. The description of a model which includes these economic features with respect to tourism as a global phenomenon has not been accomplished before in the economics literature.

2.3 International transport and the environment

Studies related to international transport and the environment are grouped into studies with a policy focus and studies with a focus on the environment.

The policy studies related to this work include a study undertaken by the International Monetary Fund (IMF; Keen, Parry and Strand, 2013) and a study undertaken by Shapiro (2016). The IMF study considers the international aviation and maritime industry jointly; the study by Shapiro takes into account all transport (via air, sea, and surface) related to the domestic and international trade of goods.

The IMF study considers a carbon tax on both the international aviation and maritime industry. The carbon tax is at Pigovian levels using a social cost of carbon (SCC) of \$25/tCO₂. Welfare calculations are based on the Harberger approximation and any cost increase which arise from the carbon tax to a transport firm are fully passed on to the consumers in the form of price increases. The study does neither consider endogenous technology uptakes in the aviation and maritime transport sector, nor general equilibrium prices and welfare effects. Under these simplifications, the study finds that the price effects from a global carbon tax on international transport would result into a 2-4% increase in aviation ticket prices and a 1% price increase of goods imports. The carbon tax could raise a revenue of approximately 22\$ billion per year in 2020, by taking into account developing

country compensation to be 40% of revenues. The study concludes by stating that a carbon price (charged per tonne of fuel purchased for consumption) not only leads to significant reductions in emissions but also exhibits potential to serve as an imperfect device to correct for other tax distortions in both industries.

The study by Shapiro (2016) uses a computable general equilibrium trade model to quantify the changes in real income in each country associated with a carbon tax of domestic and international transport. The study builds on the standard gravity in international trade, compiles a unique dataset from national commerce offices on international and intranational shipping costs, transport mode choice, pollution emissions, and trade flows for 13 sectors of production, five modes of transport and 128 countries. The policy case investigated builds on the assumption that each importing country receives the tax revenue generated by the importing country's imports in the form of a rebated lump-sum to consumers. This rebate mechanism therefore lowers the welfare implications of countries with high import levels (e.g. the US) and increases the welfare impacts of countries with relatively low levels of imports (e.g. developing countries). Using a social cost of carbon of \$29/tCO₂, the study finds that a carbon tax applied to the international maritime transport industry would increase global welfare, increase the implementing region's GDP, and decrease welfare in poor countries. Bearing in mind the limitations that arise from autarky counterfactual exercises and estimates of the social cost of carbon, the study finds that the gains from trade exceed the environmental cost of trade by two orders of magnitude.

The results in Shapiro (2016) are not informative towards determining the demand implications associated with candidate policy designs at the IMO for two reasons. First, using the tax revenues as rebated lump-sum to consumers by importing country provides a distorted view on the actual demand implications by participating country. One would need to first quantify these implications and then, based on the results obtained, design a rebate mechanism to compensate economically disadvantaged countries participating in the scheme. The rebate mechanism could take the form of rebated lump-sum to consumers, but should not necessarily be restricted to it. Second, the study takes into account all modes of transport, including air cargo transport, of all domestic as well as international transport activities. Under the UNFCCC umbrella, the IMO has a mandate for addressing CO₂ from international shipping only. Domestic emissions from shipping are therefore addressed at the national level and therefore form part of the Intended Nationally Determined Contributions (INDCs) of each Party under the Paris Agreement (see Section 2.4 below).

As will become clear in Chapter 6, the analysis undertaken in this thesis differs from the study by Shapiro (2016) in multiple ways. First, it takes into account the cost structure of transport firms on the supply side, leading to smaller price increases overall⁵. Second,

⁵A 1% price increase in fuel costs due to a carbon tax does not lead to a 1% increase in the operating costs of a transport firm due to other cost items the transport firm faces including labour, capital and material costs. By Shephard's lemma, assuming a fuel cost share of e.g. 30%, a 1% increase in fuel costs

it takes endogenous price changes into account⁶. Third, it takes technology uptakes into account. Fourth, it analyses international transport policies that are in accordance with candidate policy designs at the international organizational level, and in particular, the IMO and the ICAO. Fifth, it addresses the bulk of emissions from both international transport industries, including air passenger travel (see Table 1.1), and the demand implications in terms of tourism. And lastly, it investigates potential patterns of discrimination against economically disadvantaged countries before advising (or deciding) on an appropriate rebate mechanism to compensate these countries.

Other studies with a policy focus on international transport but without the inter-linkages of international transport with the economy have been undertaken. For example, The Economist Intelligence Unit (2008) briefing paper, commissioned by DHL Asia-Pacific, investigated the effect of oil price volatility on the value of trade using the gravity equation and 1970-2007 GDP and oil panel data. They find that a 1% increase in the price of oil leads to a 0.24% reduction in the value of trade. Another example is the study of Vivid Economics (2010), commissioned by the IMO, to quantify the economic impact of market-based measures in international ocean freight. Their method relies on estimating the elasticity of freight rates with respect to bunker prices on certain shipping routes. These estimates are then combined with elasticities of freight rates with respect to bunker prices to infer values of cost-pass through rates in international shipping markets. Their results indicate that a significant amount of the costs of market based measures in international sea transport would be borne by shipowners, as a result of low cost-pass through rates, especially in sea transport of iron ore (55%) and grains (5% to 100%). The report subsequently stimulated discussion at the IMO that market-based measures in international ocean freight would be ineffective and be discriminating against shipowners. While cost-pass through rates (as well as varying markups) certainly require thorough investigation, they do not play a distinct role in quantifying the welfare impacts associated with MBMs in shipping on a country level. This is because countries import goods from many other countries. If certain trade routes are subject to considerable higher price increases due to a full cost-pass through, the net change of the price index in the respective country would only be marginally different (if not insignificant) as it reflects the aggregate of price increases of all trade routes across countries.

There are many studies related to international transport and the environment. These include studies related to a quantification of transport emissions, and studies related to predicting future emissions using integrated assessment models (IAMs). An example of

would lead to an overall increase in transport costs of about 0.3%. Assuming competitive pricing, this increase would then also translate into a 0.3% overall price increase rather than a 1% overall price increase. To the best of my understanding, these dynamics are not taken into account in Shapiro (2016). This in turn implies that Shapiro (2016) obtains disproportionately high welfare impacts.

⁶Transport costs enter the CGE trade and tourism model as an ad valorem to supply prices. The CGE model solves for the changes in the supply prices. If supply prices change, so do transport costs. For this reason, the level of transport costs needs to be determined co-jointly with the vector of supply prices in an iterative CGE modelling framework.

the former is a study by Cristea et al. (2013), who quantify the greenhouse gas emissions from international freight transport and production. Trade data by mode of transport for the year 2004 is taken from the US Imports and Exports of Merchandise database, the Eurostats Trade database, and the Latin America (ALADI) trade database. Production emissions are taken from the GTAP model (Walmsley, Aguiar and Narayanan, 2012). The study finds that transport accounts for 33% of world-wide trade-related emissions and that tariff liberalization and GDP growth concentrated in China and India in combination with trade shifting toward more distant trading partners resulted into a growth in transport emissions which was larger than the growth in the value of merchandise trade. It should be noted that studies are regularly undertaken to quantify the emissions from international air and maritime transport at the intergovernmental level (e.g. IMO, 2014; IEA, 2015).

IAMs of the global aviation and maritime transport industry include models developed in OECD ITF (2015), Reynolds et al. (2007), and Smith et al. (2011). IAMs have a supply side focus (i.e. transport). The link to changes in consumer prices to changes in a country's overall output (in the industry and tourism sectors) and income are usually omitted. For the research undertaken in this study, these models would need to be extended to also account for price changes on the demand side and to link them with economic activity and thus welfare. A possible extension of these models is discussed in Section 7. The added value of modelling transport supply more rigorously using IAM's in a trade and tourism demand setting to the result presented in this thesis remains however questionable. The model developed in this thesis uses a simplified representation of trade and tourism demand as well as transport supply. Improving the modelling capacity of transport supply would leave the modelling capacity on the demand side unchanged and therefore result into similar aggregate welfare predictions.

Many other studies investigated the regulatory framework of environmental policies in the international aviation and maritime industries, and in particular in the aviation industry as result of its inclusion in the EU Emissions Trading Scheme (e.g. Scheelhaase and Grimme, 2007, Anger, 2010; see Section 2.4 below for the details of this scheme). None of these studies however provide a link to the tourism sector in each country and the demand implications of the economy as a result of environmental policies in the international aviation industry can therefore not be quantified.

2.4 Legal dimension of international transport policy

International shipping and aviation are excluded from Intended Nationally Determined Contributions (INDCs) which constitute the post-2020 climate targets of the landmark Paris Agreement, adopted by the twenty-first session of the Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC)

in 2015. The Paris Agreement will be implemented to "reflect equity and the principle of common but differentiated responsibilities [CBDR] and respective capabilities [RC], in the light of different national circumstances" (UNFCCC, 2015). As international transport involves the movement of goods and passengers from, across, and to many different countries around the world, the allocation of emissions from international bunker fuels cannot be allocated proportionally to the countries involved in these transport activities without complex and comprehensive regulatory frameworks. Emissions from international bunker fuels need therefore be addressed comprehensively at the global level. An intended determined contribution of the international shipping and aviation sectors would however create a conflict with the UNFCCC CBDR/RC principle, as the contributions by each country participating in the global scheme would be determined by the global scheme's mechanism to reduce the emissions, rather than by the participating nations themselves. This clash of principles was already recognised under the UNFCCC since the first meeting of the Conference of the Parties and subsequently also led to the exclusion of international aviation and shipping from the predecessor of the Paris Agreement, the Kyoto Protocol. Article 2.2 of the Kyoto Protocol stated that Annex I Parties "shall pursue limitation or reduction of emissions of greenhouse gases [...] from aviation and marine bunker fuels, working through the International Civil Aviation Organization [ICAO] and the International Maritime Organization [IMO], respectively" (UNFCCC, 1998). IMO and ICAO therefore obtained the mandate for addressing CO₂ emissions from international transport, and remained to do so in post-Paris world.

The ICAO was founded in 1947 on the premises to avoid discrimination between contracting States set forth in the Chicago convention (ICAO, 2006). The IMO was founded in 1948 on the premises to "promote the availability of shipping services to the commerce of the world without discrimination" set forth in the 1948 Geneva convention (IMO, 2017). Both the ICAO and the IMO are therefore founded on principles of non-discrimination and equal treatment. Once the ICAO and the IMO were mandated to reduce emissions from international bunker fuels, it became clear that ICAO's and IMO's principle of equal treatment and non-discrimination conflicts with the UNFCCC CBDR/RC principle. Since their nomination in 1998 to tackle these issues, both international bodies have been studying options for reducing CO₂ from international bunker fuels. Only recently however has an agreement been reached among the Member States at the ICAO to implement a carbon offsetting scheme in international aviation named "CORSIA" (Carbon Offsetting and Reduction Scheme for International Aviation; ICAO, 2016; see Section 6.4 for the details of this scheme). To this date, not commitments have been made towards reducing CO₂ from international shipping at the IMO.

At the ICAO—to comply to the extent possible with the UNFCCC's CBDR/RC principle, thereby acknowledging that the proposed scheme does not represent the position of the Parties to the UNFCCC (ICAO, 2016)—initial participation in CORSIA is voluntary. Fur-

thermore, once the offsetting scheme at ICAO becomes mandatory for its member States, least developed countries, SIDS, and landlocked developing countries will remain exempted from participation. The leading international organization in tourism is the World Tourism Organization (UNWTO). In its current framing, CORSIA does not contradict UNWTO's objectives and mission, including promoting tourism as a driver of economic growth, and implementing a global code of ethics for tourism. In a statement released in 2010 (i.e. before CORSIA was announced), the UNWTO however argues that an MBM in aviation should take into account the economic importance of tourism when it comes to impact assessments, comply with the CBDR principle, and be non-discriminatory against other modes of transport, especially on short-haul routes (UNWTO, 2016). The UNWTO also notes that although countries are exempted from the scheme, they could still be affected by it through international airlines serving both, destination markets within the scheme and destination markets of countries exempt from the scheme.

At the IMO too, concerns over discrimination against developing countries exist. Today, developing countries account for 60% of total maritime trade (ICS, 2017). Market-based measures (MBM) in international shipping could therefore affect developing countries more than developed countries and the opposition from poor countries that anticipate receiving less than their cost incurred is therefore likely to remain strong. One way to work around this issue is to implement a rebate mechanism as part of the MBM. A rebate mechanism would entitle developing countries to obtain unconditional payments (rebates) equal to the attributed burden of its participation in the scheme as e.g. proposed by Stochniol (2012). An MBM with a rebate mechanism would in theory therefore also comply with the principles of CBDR and RC under the UNFCCC umbrella. The entitlement of countries to receive a rebate and the level of the rebate could however trigger lengthy negotiations among Member States. Once an agreement has been found, it would be subject to a review after a few years as the economic condition of all Member States changes over time. An MBM with a rebate mechanism therefore creates substantial additional complexity.

Due to the shipping's inherent inter-linkages with international trade, MBMs in international shipping need to also comply with the General Agreement on Tariffs and Trade (GATT) principles under the WTO framework. For example, Article 1 of GATT (general most favoured nation treatment) states that "customs duties and charges of any kind imposed on [...] importation or exportation [...], and with respect to the method of levying such duties and charges, [...] any advantage, favour, privilege or immunity granted [...] to any product [...] shall be accorded immediately and unconditionally to the like product originating in or destined for the territories of all other contracting parties" (WTO, 1947). In other words, any (trade) advantage for one WTO Member should also apply (immediately and unconditionally) to all other WTO Member States. As long as the MBM is non-discriminatory therefore, it would in theory also comply with the WTO and GATT principles. Article III of GATT (national treatment) has attracted much more atten-

tion in recent years by academics and policy-makers as it is held applicable to *de jure* (discrimination against foreign products by origin) and *de facto* discriminatory measures (discrimination against foreign products in a domestic market) (Vranes, 2009). An MBM in international shipping may therefore be *de facto* discriminatory, as foreign goods would be priced higher than domestic goods, unless environmental policies for domestic transport are in place vis-à-vis the international scheme with equal levels of carbon prices. *De jure* discrimination of an MBM in international shipping can be avoided if all member countries participate in the scheme. Exempting countries from an MBM in international shipping complicates the interpretation of both principles significantly. Excluding (economically disadvantaged) countries from the scheme would in theory contradict the *de jure* principle and also be *de facto* discriminatory against those countries who participate in the scheme and serve the same market as the countries who are exempt. A representative of the WTO Secretariat at the IMO however concluded that a MBM in international shipping should in theory be compatible with WTO rules (IMO, 2011b) as the WTO primarily regulates and solves trade disputes among its Member States. Once the details of the policy design of a MBM in international shipping along with its exempting rules are formulated however, its compatibility with WTO rules would need to be examined in detail.

Emissions from international transport have also been tackled by other organisations. Most prominent is the inclusion of aviation CO₂ in the EU emissions trading scheme (EU ETS) since 2012. Under the EU ETS, all airlines operating to or from European airports are required to surrender allowances against their emissions. After agreement has been reached at the ICAO however to implement CORSIA from 2012 onwards, the European Commission (EC) decided to limit the scope of the EU ETS to flights within the European Economic Area (EEA) until 2016 and issued a proposal in 2017 to continue to do so beyond 2016 (EC, 2017a). The EU ETS is fully compatible with the UNFCCC CBDR/RC principle as it's scope is limited to EEA flights only.

To this date, no environmental policy schemes have been put into place by other organisations to tackle the emissions from international transport. The EC is calling for a global approach to reducing greenhouse gas emissions from international shipping, working through the IMO (EC, 2017b), but also gives consideration to include emissions from international shipping into the EU ETS (ICS, 2017). The EC's push forward to reducing emissions from aviation stimulated much of the political debate needed to achieve an agreement at the international level. The EU ETS is therefore most likely the primary reason why an agreement to tackle emissions from international transport has already been reached at the ICAO, while the debate at the IMO is still ongoing. If no progress is made at the IMO, unilateral action to tackle the emissions from international shipping could not only come from the EC but also from Canada, California, or China, as they already introduced carbon pricing at the national level (ICS, 2017). Enacting environmental policies at the national level would however greatly undermine the authority of the IMO.

MBMs for international aviation and maritime bunker fuels have also been proposed as an innovative source of global climate finance. Article 9 of the Paris Agreement defines climate finance as the financial resource from developed country Parties that is needed to assist developing country Parties with respect to mitigation and adaptation to climate change, in continuation of their existing obligations under the Convention (UNFCCC, 2015). The agreed collective quantified goal is to raise 100\$ billion per year. A report from the World Bank, in close partnership with the IMF, the OECD and the Regional Development Banks, states that a carbon tax of 25\$ per tonne of CO₂ in both the aviation and maritime transport industries would raise 40\$ billion per year by 2020 (World Bank, 2011), subject to the agreed level of compensation needed for developing countries who participate in the scheme. MBM's in international transport could therefore provide meaningful contributions to mobilising funds to mitigate and adapt to climate change.

Chapter 3

Methodology

This thesis builds on gravity models of international trade and tourism and uses comparative static exercises to show the welfare implications associated with a carbon emissions pricing scheme in international transport.

Gravity equations are consistent with economic theory, relatively easy to implement econometrically and have been used for quantifying welfare impacts of trade policy changes for many years (see Section 2.1). Today, they are considered in combination with the many possible underlying micro-theoretical foundations but identical macro-level predictors, as one of the most empirically robust and theoretically sound findings in all of economics (Head and Mayer, 2014, Costinot and Rodríguez-Clare, 2014).

First demonstrated by Dekle, Eaton and Kortum (2008) and similar to older computational general equilibrium (CGE) models (Baldwin and Venables, 1995), quantitative models based on structural gravity can be used to evaluate policy changes by introducing a shock to any of the gravity variables and then solving a system of non-linear equations to obtain the state of a new equilibrium.

In equilibrium, supply equals demand. Drawing from economic theory, gravity equations can be used to explain consumer demand using equilibrium prices and multilateral resistance terms. In international trade, the demand side is represented by import expenditures of goods produced in foreign countries. In international tourism, the demand side is represented by tourism expenditures in foreign countries. As both these variables take into account transport costs, gravity models naturally take into account an equilibrium price inclusive of transport costs to explain changes in demand.

The point of departure for this analysis are therefore theory-consistent, multi-country gravity models of international trade and tourism.

Current practice in modelling exercises using gravity equations generally involves four

steps: (1) the measurement of variables of interest, (2) the establishment of data-informed theory and models, (3) the estimation of key structural parameters of those models, and (4) the evaluation of policy questions using counterfactual exercises.

Chapter 4 develops a theoretical framework for international trade, Chapter 5 a theoretical framework for international tourism. Chapter 6 combines both theoretical frameworks and specifies the cost component on the supply side in more detail to be able to account for exogenous price shocks induced by environmental policies. This chapter provides a general overview of the modelling exercises in Chapters 4-6 by explaining each of the aforementioned steps 1 to 4.

1 Measurement. The variables of interest are bilateral demand variables (country by country trade and tourism flows), bilateral variables explaining demand (transport costs) and country specific variables measuring a country's economic activity (gross output, income, and expenditure).

There exist many sources of data measuring global flows, with limitations however with respect to worldwide coverage and aggregation levels. The dataset in this study therefore draws from information and variables collected from different data sources.

Commonly reported by statistical authorities are the demand variables "import values" and "international tourism receipts". In international trade, the import value corresponds to the statistical value, inclusive of transport costs (CIF¹), that is declared on the customs declaration form. In international tourism, the statistical value corresponds to balance of payments (BOP) expenditures of goods and services by international inbound visitors (international arrivals). A detailed description of these variables can be found in the relevant Chapters 4 and 5, and Appendices A and B.

More difficult to measure are supply prices in the partner country and bilateral transport costs between the reporting and partner country as these are usually not reported by statistical authorities. In international trade, the supply price corresponds to the cost of production at the factory gate in the origin country (assuming no markup). In international tourism, the supply price corresponds to the costs paid for all tourism activities (lodging, food, services) in the destination country (exclusive of travel costs). Bilateral transport costs² refer to the costs to ship manufacturing produces from the origin (the exporting) to the destination country (the importing country), or, to the costs to travel from the origin (the outbound) to the destination country (the inbound tourism country) respectively. In

¹The statistical value is 'the amount that would be invoiced in the event of sale or purchase at the national border of the reporting country' (Eurostat, 2014). For exports, this value is said to be a FOB (free on board) valuation, for imports a CIF (cost, insurance, freight) valuation.

²Transport costs in international trade include shipping costs, distribution and logistic costs (handling, loading and unloading, storing, packaging, and warehousing costs), probability of loss or damage, and the time the traded goods are locked in transit. Transport costs in international tourism are the costs paid for a ticket for a return trip inclusive of taxes, surcharges and other fees.

either case, both variables - supply prices and transport costs - are needed to calculate bilateral transport costs *relative to* supply prices in the partner country. Transport costs are usually not reported in bilateral trade and tourism data and need therefore be collected from other data sources.

Lastly, country specific variables measuring a country's economic output in manufacturing (trade) and service provision (tourism) are needed to link changes in bilateral flows to changes in welfare. Gross manufacturing output data can be obtained from UNIDO statistics, gross industry output data from the OECD input-output tables. Missing values can be approximated by the ratio of value added to manufacturing value added in GDP as in Mayer and Thoenig (2016) or by estimating the ratio of GDP to gross output using GDP and population as independent variables as in Simonovska and Waugh (2014). Gross tourism output can be measured by adding aggregated international tourism expenditures to domestic tourism receipts as reported by the WTTC. These variables are described in detail in each chapter.

The data requirements of this study are substantial. The collected data however ensures that the computed results are based on actual measurements (or approximations therefore in case of missing data) of the key variables of interest. Conditional on the data³ and the model restrictions imposed by economic theory, the CGE model developed in this thesis should therefore be capable to predict approximate changes in economic activity as a result of carbon emission pricing schemes in international transport.

2 Theory: Theoretical frameworks in the economics discipline often build on functional forms to specify a relationship between the explained and explanatory variables. These include linear and logarithmic functions, but also Cobb-Douglas, Constant Elasticity of Substitution (CES), and Leontief functions. Building on consumer theory, one of these functions is then selected and specified in way to describe aggregate consumer preferences. In doing so, they are then referred to as utility functions and build on the underlying assumption of consumers to act rationally. The next step involves the maximisation of consumer utility by setting the first derivative equal to zero and solving for the variable of interest (e.g. quantity) to obtain a consumer demand equation. The aggregate demand equation is then immediately obtained by (1) solving for equilibrium prices that are representative of all consumers and (2) integrating over all bundles of goods or activities consumed. Finally, assuming that supply equals demand, the model can be closed using a market clearing condition.

Theoretical frameworks in economics often impose that in a general equilibrium, consumers

³Data limitations are unavoidable and so is the models worldwide coverage and predictability. Bilateral global flows reveal the matching of supply and demand. However, not all countries engage with each other in terms of trade and tourism activities which thus results into zero flows. These flows are often not reported. Missing observations in the data could either be a result of actual zero flows or missing observations, both of which are not taken into account in this modelling exercise. Irrespective of their ultimate cause and price increases therefore, zero flows remain zero in the counterfactual equilibrium.

maximise utility (demand), firms maximise profits (supply), and markets clear (equilibrium prices). The theoretical frameworks developed in Chapters 4 and 5 have in common this market clearing condition.

3 Estimation: In theoretical frameworks designed to explain global flows, the explained variables are the bilateral demand variables and the explanatory variables are the price variables and price indexes (also referred to as multilateral resistance terms). The logarithmic transformation of the gravity equation allows to measure changes in demand in response to changes in prices or changes in transport costs respectively. The structural model parameters of the gravity equations are therefore price elasticities of demand. These parameters can be estimated using bilateral expenditure and price data. Once estimated, they can be used to predict changes in trade and tourism expenditures associated with e.g. price changes due to carbon emission pricing schemes in international transport and are therefore key parameters of this thesis.

Since the influential paper of Anderson and Wincoop (2003), specifications of theory-consistent gravity equations include multilateral resistance terms (referred to as structural gravity equations, see Head and Mayer, 2014). In the most simplistic form, the multilateral resistance terms take the form of price indexes. Price indexes consist of prices and expenditure shares in each country, including both domestic and foreign expenditures. The multilateral resistance terms are therefore endogenous and take the form of country fixed effects in regressions. This has two important implications. First, demand elasticities cannot be measured from prices which are purely country specific, as they are absorbed by the fixed effects in the regression. One popular way to estimate the price elasticity of demand in gravity equations has therefore been using bilateral costs data such as tariffs or transport costs. If these variables are specified as the one plus the ad valorem price equivalent (iceberg costs), the coefficient estimate represents the price elasticity of demand. The transformation of the bilateral cost elements into ad valorem price equivalents ensures that the price elasticity of demand with respect to bilateral tariff or transport costs is equivalent to the price elasticity of demand with respect to prices. Second, estimating gravity equations does not require to collect data on country specific prices (which are usually difficult to obtain), as these are absorbed by the country fixed effects in the regression. The former complicates the measurement of structural model parameters, whereas the latter eases the use of gravity equations in a policy context and significantly contributed to its rapid uptake in the literature.

The gravity structure imposes the restriction to specific the price elasticity of demand to be common to all country pairs in the dataset. In theory, the price elasticity of demand varies by country pair, with some country pairs having a higher demand elasticity than others. Estimating all these elasticities in the gravity setting would however result into as many variables as observations. Constructing theoretical frameworks on the one hand and empirical estimation of key structural parameters thereof on the other therefore involves a

balancing act: quantitative models must be rich enough to speak to primary features of the data, yet parsimonious enough to allow for estimating its structural parameters (Costinot and Rodríguez-Clare, 2014) and can never be exact.

4 Counterfactual analysis: Quantitative models based on structural gravity are similar to older CGE models (Baldwin and Venables, 1995) in their primary focus to evaluate policy changes using economic data (Costinot and Rodríguez-Clare, 2014). Common starting point are theoretical models that respond to data in a way that can be described by its estimated parameters. Given that the observed data essentially reflects an equilibrium state of supply matching demand, the model and original dataset describe an initial equilibrium state. Counterfactual exercises then involve introducing a shock to any of the variables of the model and solving for a state of a new equilibrium.

If gravity equations meet the separability requirement in terms of labour endowments in the home country (see Chapters 4 and 5), counterfactual changes in income can be derived by solving a system of non-linear equations which require information of only three statistics: the expenditure shares on goods from different countries, initial income (output) levels, and structural parameters of the model including the demand elasticity. The first two are observed in the data, the latter can be obtained from empirical exercises as described above. The changes in income levels then reveal changes in expenditure, which, in combination with changes in prices, can be linked to changes in real income and thus welfare. This approach was first demonstrated by Dekle, Eaton and Kortum (2008) and has been termed “exact hat algebra” by Costinot and Rodríguez-Clare (2014). Chapters 4-6, make use of this approach to calculate changes in real income associated with foreign price shocks in trade and tourism. In Chapter 6, these price shocks take the form of a global bunker fuel levy charged per tonne of fuel purchased for consumption in the international aviation and maritime industry.

Chapter 4

Model of international trade

This chapter develops a theoretical framework of consumer demand to explain international trade flows by mode of transport. It describes a world economy consisting of multiple firms in each country, where each firm produces a unique variety and chooses a cost optimum transport mode for exporting it. Consumers consume at least a little of each variety in bundles, where each bundle represents the group of varieties transported using a common transport mode. Because consumers maximise utility and firms minimise costs, the theoretical framework consists of a consumer demand equation as well as a production supply equation that exhibits a multinomial logit structure.

This chapter focuses on international seaborne and airborne trade and describes column 2 of Table 1.1. Chapter 6, which follows after this chapter, focuses on international tourism, representing column 3 of Table 1.1.

4.1 Background

International trade has been shaped by rapid growth in vertically differentiated products as a result of vertical specialisation (Yi, 2003; Fajgelbaum, Grossman and Helpman, 2011; Zhu, Yamano and Cimper, 2011). Because firms increasingly specialise in only one particular innovation or production process, their manufacturing output is often not a final but an intermediate good, which may be used in an entire range of differentiated products. The today's global supply chain is therefore a conglomerate of a complex interwoven network of many stakeholders, including high-tech firms, OEM's, and retailers, and spans over several countries.

Transport is central to the functioning of these global supply chains. Globalisation and its drive for increased competition on the one hand, as well as differences in unit labour costs and cost optimisations of firms on the other, makes it necessary for firms to collaborate

even if they are far distant from each other¹. Given the vast range of vertically differentiated products and their special product characteristics, the transport of these globally exchanged goods needs to be accomplished by different transport modes that are capable of bridging long-distances in a cost-effective manner.

Time is money. The non-accessibility of goods in transit is costly for a firm. Even more so, the higher the unit value² of the good. Hummels and Schaur (2013) find that each day in transit is worth 0.6 to 2.1 percent of this value and that long transit delays significantly reduce the probability of firms to successfully participate in the export market. Yet, time costs associated with the export of goods do not always play a distinctive role in international trade. Cheap stuff needs to remain cheap in order to be able to get sold in foreign markets competitively. It's price is in part also determined by the costs associated with exporting it and rules out the possibility to use expensive shipping methods. The availability of fast but expensive and slow but inexpensive transport modes in international trade therefore comes as a direct result of highly specialised manufacturing process and the collaboration of firms in a globalised world.

The most prominent but also most cost diverse transport modes in international trade are sea and air transport. While freight rates by air are seven times higher than by sea³, the transport of goods by air is accomplished in only a fraction of the time. The link between differentiated transport modes and differentiated products is in most cases therefore straightforwardly determined. Given that transport costs must remain relatively small in comparison to the goods' value, products with relatively higher unit values⁴ tend to be transported by faster means of transport (air transport), whereas products with relatively lower unit values tend to be transport by cost-effective means of transport to utilise economies of scale (sea transport).

Vertical specialisation entails differentiation by products and transport modes. Splitting a product into intermediates inevitably results into some parts that are more valuable than others. The range of the per unit values of intermediates therefore increases the higher the level of product differentiation. One of the fundamental consequences of growth in vertically differentiated products is the changing landscape of a higher diversity of products

¹First shown by Helpman (1981), intra-industry trade is related to differences in income per capita, which, on the other hand, determine the volume of trade. More recent research shows that for a given product category with many trading partners, higher-income countries tend to export goods with higher unit values (Schott, 2004) as well as to import goods of higher quality (Bils and Klenow, 2001).

²For a given product category, the per unit value of a traded good can be obtained by dividing the import value in US dollars by the import quantity in tonnes. Table A.1 shows that these value-to-weight ratios differ by two orders of magnitude by subdividing extra-EU manufacturing imports into only 16 product categories.

³Hummels and Schaur (2013) indicate that, on average, ocean and air freight rates vary by a factor of 6.5. This study suggests a factor of 8 (see Section 4.3).

⁴For a given product category, the per unit value of a traded good can be obtained by dividing the import value in US dollars by the imported quantity in tonnes. See Table A.1 for average value-to-weight ratios by industry.

exchanged globally. An increasing share of goods with relatively higher unit values will therefore materialise into the global manufacturing and transport industries. If this pattern continues, time will play an increasingly important role in international trade, as evidenced by changes in the past: In combination with low fuel prices, container ships have been designed to go faster (Wright, 2010), and the growth in total airborne trade⁵ has outpaced the growth in total seaborne trade since records began in 1975 (Figure A.5).

The availability and use of different transport modes generates another source of product differentiation⁶ in international trade. A firm participating in export markets differentiates the products "air" and "sea transport" by cost and time. A firm's selection over these differentiated transport modes is therefore a discrete choice. To learn about the export preferences of such firms and the relative importance of time and transport costs in international trade, I formulate in this chapter a discrete choice model that is embedded into a general equilibrium trade model. In a second step, I show how to translate this model into a form that can be used for empirical work using international trade data by mode of transport. The results indicate a strong influence of the time sensitivity of goods on the general preference of air over sea transport.

The theoretical framework set out in this study builds on the Krugman (1980) model with monopolistic competition and many firms and takes into account the marginal costs of production inclusive of transport and time costs. It therefore adds to existing specifications⁷ a component of time cost that reflects the capital cost of goods locked up in transit. The firm's cost function is then specified to be cost-minimising in the aggregate, including both transport *and* time costs. Conditional on these cost elements, a firm might therefore select a transport mode with higher per unit transport costs but lower per unit time costs to export to foreign markets. In doing so, firms choose from a set of distinctive transport modes that have idiosyncratic appeal. Drawing on the theory of McFadden (1973) and Anderson, De Palma and Thisse (1992), the assumed form of the transport utility function and the distribution of firms' tastes are such that the system of aggregate transport demand exhibits a multinomial logit structure.

The only study to additionally account for transit time in international trade is Hummels and Schaur (2013). Yet, their specification relies on measuring time cost in units of days (i.e. an indirect measure of time costs). In this study, time costs are measured using the concept of the value of time (VOT), which is defined as the marginal rate of substitution between transit time and transport cost. Time costs are therefore expressed in monetary

⁵The growth in Figure A.5 implies that air transport has had a significant influence in enabling the fast and secure means of transport of goods with higher unit values as a result of vertical specialisation. Annual global revenue tonne-kilometres (RTK) of air transport remain however much smaller than annual global RTK of sea transport. In 2013, airborne trade represented 0.17% of seaborne trade by annual global RTK.

⁶First formulated by McFadden (1973).

⁷These include Harrigan, 1995, Harrigan, 2010, Lux, 2011, Hummels and Schaur, 2013, and Allen and Arkolakis, 2014

units and can therefore be simply added to the marginal cost function of a firm to model differences in trade costs of airborne and seaborne trade. In this way, the model and estimated parameters can also be used to investigate the relative contribution of fast moving goods on the welfare gains from trade.

The results in this chapter indicate that the VOT varies between industries and differs between airborne and seaborne trade by factors of hundreds. The estimated VOT for the total of manufacturing airborne trade is 50, whereas, for seaborne trade, the estimated VOT is only about 0.3 Euros per tonne per hour. Given these inherent differences, I use counterfactual exercises to investigate two related policy cases in international trade and transport. The first policy case considers slow steaming. The contribution of ships to the CO₂ emissions from international trade is significant (Table 4.3). Given its anytime availability, applicability, and significance, regulated slow steaming is considered to be one of the key mitigation options to reduce CO₂ from international maritime transport⁸. I show in this chapter that slow steaming could reduce the CO₂ emissions from international trade by a significant amount and with only little impacts on welfare. The second policy case is hypothetical and considers a change from all air to sea cargo transport. In this case, the results are indicative of the relative contribution of aviation to the welfare gains from trade, which I estimate to be, on average, as large as 30%.

The limitations of the presented study originate from model simplifications and data constraints. I describe a theoretical framework in which time costs are assumed to predominately influence the marginal costs of production. The model does therefore not explicitly account for fixed exporting costs, extensive margins (Chaney, 2008) and any potential influence thereof in terms of time costs. Furthermore, this study does not look into the determinants of global manufacturing patterns and the implications in terms of manufacturing production in general and per capita income in particular. Instead, the counterfactual exercises in this study assume that the global manufacturing patterns in vertically differentiated products remain unchanged. The results in this study are therefore partial equilibrium results with respect to changes in transport and time costs and should therefore only be used as an informative benchmark. In addition, and as a direct result of data constraints, this study does not incorporate any components of the logistic supply chain beyond transport and time costs into a firms cost function. The logistic supply chain in international transport is a complex construct involving a significant number of economic agents and decision makers. The multinomial logit model presented in this chapter can therefore only be a simplification of these processes. By referring to the firm as a decision marker in the text, I equally address shippers and other economic agents involved in the decision process.

⁸After the financial crises in 2008, slow steaming has been widely used in the maritime transport industry as a measure to balance excess supply in ship capacity with the downturn in trade demand, which resulted into significant reductions in CO₂ (IMO, 2014)

The remainder of this chapter is organised as follows. The next section presents the theoretical framework. Before taking the model to data, I describe the dataset in Section 4.3, which I use to estimate the value of time in Section 4.4 and to quantify the relative importance of time costs in international trade in Section 4.5. In the section after that I use counterfactual exercises to show the welfare impacts associated with the policy cases described above before I summarise my results.

4.2 Theoretical framework

In this section, I develop a general equilibrium framework of international trade, which incorporates firm-level preferences of choosing cost-effective transport modes for exporting. The model consists of two components. The demand side is represented by the traditional gravity equation of international trade, whereas the supply side is represented by a multinomial logit model of discrete choice. Both models are linked using equilibrium prices.

I build on the Krugman (1980) model with monopolistic competition and many firms in one country and where each firm produces a unique variety indexed by $\omega \in \Omega$. I deviate from the Krugman model by additionally assuming that each variety exhibits product attributes that are unique. Conditional on these attributes, a firm chooses a transport mode m that is minimising in trade and time costs. By ω I therefore refer to an individual firm producing a unique variety, which is transported using a characteristic transport mode. The number of varieties exhibiting the same transport mode can therefore be indexed using $\omega \in \Omega^m$. In what follows, I consider an infinite number of varieties but a finite number of available transport modes.

Setup. I consider a world economy comprising $i = 1, \dots, I$ countries and labour L as the only factor of production with factor income (wage) denoted as w . The number of firms in each country is denoted N_i and determined in equilibrium. Their fixed cost of entry in order to produce is f_i^e . Firms in each country are confronted with increasing returns to scale (IRS) in production but constant returns to scale (CRS) in international transport.

The transport of goods between countries is accomplished by different modes of transport. The transport modes considered by a firm in country i to export to country j is a subset of the universal set M of transport alternatives in the economy and given by $m \in \mathcal{C}_{ij}$, where $\mathcal{C}_{ij} \subset M$ denotes the choice set, which is ij -specific.

Demand. Consumers have CES preferences over varieties ω . As each variety is transported using a characteristic transport mode m , consumers consuming different quantities of varieties $q(\omega)$ therefore indirectly select different transport modes for those varieties to be imported. I group the varieties exhibiting the same transport mode m into bundles

$\omega \in \Omega^m$ and assume that a representative consumer in country j has a *predetermined* budget share α^m available for consuming that bundle. Consumers therefore maximise their utility according to a two-tier utility function. The upper-level is Cobb-Douglas

$$U_j = \prod_{m=1}^M (U_j^m)^{\alpha_j^m}, \quad \text{where} \quad \sum_{m=1}^M \alpha_j^m = 1. \quad (4.1)$$

The lower-level utility function is CES

$$U_j^m = \left(\sum_{i=1}^I \int_{\omega \in \Omega_i^m} q_{ij}(\omega)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}}, \quad (4.2)$$

where $\Omega^m \subset \Omega$ and $q_{ij}(\omega \in \Omega^m)$ is the quantity demanded of varieties produced in country i and consumed in country j . Common to all consumer bundles and countries is the elasticity of substitution between goods $\sigma > 1$.

Putting a constant share by transport mode into the utility function is unconventional. This specification is however necessary to establish an equilibrium condition between consumer demand and transport supply by mode of transport. The equilibrium condition implies that the cost-optimum selection of transport modes by firms is such that it exactly matches the consumer demands for the bundles of goods imported by these different transport modes. If supply and demand are not equilibrium, this condition may be problematic as the bundle $\omega \in \Omega^m$ demanded may be different from the actual quantities imported using transport mode m .

Assuming equilibrium conditions, the CES demand function for each individual bundle is given by

$$q_{ij}(\omega \in \Omega_i^m) = p_{ij}^{-\sigma}(\omega \in \Omega_i^m) X_j \alpha_j^m (P_j^m)^{\sigma-1}, \quad (4.3)$$

where $X_j \alpha_j^m$ is country j 's total expenditure on bundle m goods and P_j^m is the bundle or mode-specific Dixit-Stiglitz price index

$$P_j^m \equiv \left(\sum_{i=1}^I \int_{\omega \in \Omega_i^m} p_{ij}^{1-\sigma}(\omega) d\omega \right)^{\frac{1}{1-\sigma}}. \quad (4.4)$$

Mode-specific bilateral trade flows can then be determined by multiplying the CES demand function by the price p_{ij} and subsequently integrating over all varieties

$$X_{ij}^m \equiv X_j \alpha_j^m (P_j^m)^{\sigma-1} \int_{\omega \in \Omega_i^m} p_{ij}^{1-\sigma}(\omega) d\omega, \quad (4.5)$$

where $X_{ij}^m \equiv \int_{\omega \in \Omega_i^m} q_{ij}(\omega \in \Omega_i^m) p_{ij}^{1-\sigma}(\omega) d\omega$. If the bundles by transport mode were to reflect a common set of varieties associated with an economic sector (say h), i.e. $\Omega_i^m \equiv \Omega_i^h$, Equation 4.5 would represent a sector level version of multi-sector gravity models commonly

used in the literature (see e.g. Donaldson, 2010, Costinot and Rodríguez-Clare, 2014, Caliendo and Parro, 2015). In this case however, the bundles $\omega \in \Omega_i^m$ represent goods imported from all partner countries using a common transport mode m , irrespective of their final use in the importing country. A bundle $\omega \in \Omega_i^m$ therefore spans over the entire range of representative economic sectors in country j . Yet, because the consumer bundles only differ in prices, it is possible to aggregate over all consumer bundles to obtain the aggregated value of total bilateral trade flows between country i and j . Under Cobb-Douglas preferences, the aggregate consumer price index in country j is given by

$$P_j \equiv \prod_{m=1}^M (P_j^m)^{\alpha_j^m}. \quad (4.6)$$

Replacing P_j^m with the demand equation for each bundle in 4.5 yields into the total demand equation

$$\begin{aligned} P_j^{1-\sigma} &= \prod_{m=1}^M (P_j^m)^{(1-\sigma)\alpha_j^m} \\ &= X_j \prod_{m=1}^M \left(\frac{\alpha_j^m}{X_{ij}^m} \int_{\omega \in \Omega_i^m} p_{ij}^{1-\sigma}(\omega) d\omega \right)^{\alpha_j^m} \iff \\ X_{ij} &= X_j P_j^{\sigma-1} \prod_{m=1}^M \left(\frac{\alpha_j^m}{\lambda_{ij}^m} \int_{\omega \in \Omega_i^m} p_{ij}^{1-\sigma}(\omega) d\omega \right)^{\alpha_j^m}, \end{aligned} \quad (4.7)$$

where

$$\lambda_{ij}^m = \frac{X_{ij}^m}{X_j} = \frac{X_{ij}^m}{\sum_{m=1}^M X_{ij}^m} \quad (4.8)$$

is the expenditure share of country j on the bundle of goods imported using transport mode m from country i or, in short, the bilateral mode-specific expenditure share⁹. For Equation 4.7 to hold in a general equilibrium therefore, λ_{ij}^m must be determined independent of j 's labour endowment $w_j L_j$. At this point however, it is not known what constitutes prices $p_{ij}(\omega)$ and trade flows X_{ij}^m , which thus leads to the following proposition.

PROPOSITION 1: *Bilateral mode-specific expenditure shares are entirely determined by relative differences in j 's pre-determined budget share, mode-specific bilateral transport costs, and the number of firms exporting to j using transport mode m .* Proof: see Equation 4.27.

Proposition 1 is similar to the proposition in Lux (2011) and ensures that mode-specific bilateral trade shares λ_{ij}^m remain multiplicatively separable. Because λ_{ij}^m varies by country pair however, there is a need to keep track of it in the model.

The next step involves solving for optimal prices $p_{ij}(\omega)$ before integrating over all varieties $\omega \in \Omega_i^m$ to obtain a gravity-like equation of international trade by mode of transport.

⁹Lux (2011) uses a similar specification for this expenditure share.

Supply. Each manufactured good can be produced everywhere. However, exporting countries differ in terms of their production costs due to differences in labour and productivity z . Under monopolistic competition with homogeneous firms, productivity varies by country, but not within a country. All firms in country i therefore share the same productivity level z_i to produce one unit of the good using $1/z_i$ units of labour. The marginal cost of producing the quantities $Q \equiv \{q_j\}$ by a representative firm in country i using wage w_i is therefore $w_i q_j(\omega)/z_i$.

For manufactured goods to be sold in foreign markets, the costs borne by a firm include the costs for exporting. Exporting costs contain transport costs as well as the capital costs of goods tied up in transit, both of which are dependent on the variety $\omega \in \Omega^m$, as each variety is transported using a characteristic transport mode m . However, for the transport of goods to foreign markets, international transport carriers are assumed to charge a per-unit transport price, which is independent of the product type and therefore variety shipped¹⁰.

Faced with marginal production and exporting costs, the cost function of a firm located in i with exports to j is

$$C_{ij}^m(\omega) = q_{ij}(\omega) \left(\frac{w_i}{z_i} \tau_{ij}^m \right) + w_i f_i^e, \quad (4.9)$$

with marginal costs given by

$$MC_{ij}^m = \frac{w_i}{z_i} \tau_{ij}^m. \quad (4.10)$$

The following equations specify how time costs enter the cost function before turning to the interpretation and discussion of the role of fixed costs f_i^e in Equation 4.9.

τ_{ij} are mode-specific iceberg transport costs a firm faces in shipping one unit of the variety $\omega \in \Omega^m$ from i to j , which enter the gravity equation as an ad valorem tax equivalent to the production costs at the factory gate w_i/z_i

$$\tau_{ij}^m \equiv 1 + \frac{t_{ij}^m + s_{ij}^m}{w_i/z_i}, \quad (4.11)$$

where $\tau_{ii}^m = 1$ and $\tau_{ij}^m \geq 1$.

Iceberg transport costs consist of mode-specific per-unit transport costs t_{ij}^m and mode-specific per-unit time costs s_{ij}^m —similar to a shadow price—reflecting the capital costs of goods tied up in transit. In particular, the time costs are given by

$$s_{ij}^m = VOT^m \cdot TT_{ij}^m, \quad (4.12)$$

¹⁰Certain types of varieties of goods transported might require special packaging, handling, insurance, etc. and the transport and time costs are therefore dependent on the variety shipped. Due to limited information on these costs however, I do not explicitly account for such cost differences by product type.

where TT_{ij}^m is the mode-specific transit time and VOT is the value of transit time common to all firms on the bundle of m goods and defined as the marginal rate of substitution between transit time and transport cost

$$VOT^m = \frac{\partial MC_{ij}^m / \partial TT_{ij}^m}{\partial MC_{ij}^m / \partial t_{ij}^m} \quad (4.13)$$

in units of [€/units/hour]. Due the addition of the shadow price in the cost function, it might be cost-effective for a firm to choose a transport mode with higher per unit transport costs but lower per unit time costs (e.g. choosing air over sea transport).

Transit time TT is the duration the good remains on the transport vehicle. During this time, the good is non-accessible and can therefore not be sold to the customer. The cost associated with transit time is therefore the opportunity cost of having goods tied up in transit¹¹.

The VOT is used to express time as an economic value, the interpretation of which depends on the specification of the VOT. If the VOT is specified among all transport alternatives, time is considered as a homogeneous resource (a shadow price), which is uniform across all alternatives (DeSarpa, 1971; Truong and Hensher, 1985). If the VOT is specified for each transport alternative as in the case above, time is interpreted as a resource comparable with a factor input into a production function for the transit activity (DeSarpa, 1971). The VOT therefore accounts for the opportunity cost of making goods accessible at an earlier or later point in time that arises from perishability, insurance costs (and thus transport risks) and capital carrying costs¹².

The interpretation of the role of fixed costs f_i^e in the cost function in Equation 4.9 is crucial. With fixed costs, there are increasing returns to transport mode. That is, the cost of quantity shipped by a given transport mode also depends on the quantity shipped by other modes. A key question to resolve is therefore the role of interdependencies between choices of transport mode. From a theoretical point of view, the interdependency is important to consider because of increasing returns. From an empirical point of view however, this interdependency is overruled because of data limitations. Section 4.4 estimates the VOT using trade data by mode of transport. Because this data only reveals transport choices in aggregated form by country, the estimation procedure imposes the IIA property on the model. As a result, the disturbances between transport modes are assumed to be mutually independent. The consideration of increasing returns to transport mode would contradict the IIA property needed for estimation. To make the estimated results compliant with the theory outlined in this section, fixed costs are assumed to appear in production but not in

¹¹The opportunity cost of goods tied up in transit is the difference between the present value and the discounted present value of the commodities at the time of arrival, subject to a discount rate.

¹²If the VOT per day is expressed in percent of the goods value tied up in transit, it can also be interpreted as a daily discount rate.

transport. This is why fixed costs f_i^e obtain the index i instead of ij in Equation 4.9. As a result, the model considers IRS in production but CRS in transport.

Faced with the cost function in Equation 4.9, firms utilise an optimisation sequence¹³ in which they initially

1. minimise their per-unit production costs by selecting the transport mode m with lower marginal costs (MC_{ij}^m) under CRS, and then
2. maximise their production output ($q_{ij}(\omega)$) by charging an optimal price under IRS.

In other words, firms maximise profits once the transport decision has been made. The transport decision (Step 1) is purely based on differences in marginal costs MC_{ij}^m between transport modes, including marginal transport and time costs. Fixed costs and increasing returns to transport mode are not considered in these choices. Fixed costs and increasing returns to production (as is standard in the Krugman model) do however matter once the firm maximises its production output and are therefore taken into account in addition to the marginal costs in the profit maximising function in Step 2.

Step 1: minimise per-unit production costs. Firms minimise marginal costs by choosing a transport mode m , which yields the optimal cost combination of transport and time costs, t_{ij}^m and s_{ij}^m . The probability of a firm located in i to choose m to ship to j (denoted $\mathbb{P}_{ij}(m)$) is therefore equal to the probability that the marginal costs using transport alternative m are lower than or equal to the marginal costs from all available transport alternatives k in the choice set \mathcal{C} . Mathematically

$$\begin{aligned}\mathbb{P}_{ij}(m|\mathcal{C}_{ij}) &= \mathbb{P}\left[MC_{ij}^m \leq MC_{ij}^k, \forall k \in \mathcal{C}_{ij}, k \neq m\right] \\ \mathbb{P}_{ij}(m|\mathcal{C}_{ij}) &= \mathbb{P}\left[t_{ij}^m + s_{ij}^m \leq t_{ij}^k + s_{ij}^k, \forall k \in \mathcal{C}_{ij}, k \neq m\right] \\ \mathbb{P}_{ij}(m|\mathcal{C}_{ij}) &= \mathbb{P}\left[t_{ij}^m + VOT^m \cdot TT_{ij}^m \leq t_{ij}^k + VOT^m \cdot TT_{ij}^k, \forall k \in \mathcal{C}_{ij}, k \neq m\right].\end{aligned}\tag{4.14}$$

Because the marginal cost of production $w_i q_j(\omega)/z_i$ for a given variety ω are independent of the transport mode, they become irrelevant in the respective choice situation. The choice probabilities of the different transport alternatives are therefore only described by the differences in transport and time costs.

The systematic cost component of the marginal cost function of a firm (denoted V_{ij}^m) therefore only needs to include the generic variables t_{ij}^m and s_{ij}^m

$$V_{ij}^m = \beta_0^m + \beta_3^m (t_{ij}^m + VOT^m \cdot TT_{ij}^m),\tag{4.15}$$

where β_0^m is an alternative-specific constant and β_3^m is the coefficient of transport cost and defined as $\beta_3 \equiv \partial V_{ij}^m / \partial t_{ij}^m$. To be compliant with the definition of the VOT in 4.13, the

¹³The definition of optimisation sequences is not uncommon in the international trade literature. For a recent study see e.g. Antràs, Fort and Tintelnot (2017).

ratio of the coefficient of transit time to transport cost must be equivalent to the value of time, in this case $VOT^m \equiv \beta_2^m / \beta_3^m$, where β_2^m is the coefficient of transit time and therefore given by $\beta_2^m \equiv \partial V_{ij}^m / \partial TT_{ij}^m$.

Assuming that systematic differences in marginal costs $V_{ij}^m - V_{ij}^k$ can be described by the random differences $\varepsilon_{kij} - \varepsilon_{mij}$, such that $V_{mij} - V_{kij} \leq \varepsilon_k - \varepsilon_m$, which are i.i.d. and Gumbel-distributed with location parameter η and a scale parameter¹⁴ $\mu > 0$, mathematically $\exp[-e^{-\mu(\varepsilon-\eta)}]$, yields into the multinomial logit (MNL) model (McFadden, 1973)

$$\mathbb{P}_{ij}(m \in \mathcal{C}_{ij} | t_{ij}, TT_{ij}) = \frac{e^{\mu V_{ij}^m}}{\sum_{m \in \mathcal{C}_{ij}}^M e^{\mu V_{ij}^m}}, \quad (4.16)$$

where $\mathbb{P}_{ij}(m \in \mathcal{C}_{ij} | t_{ij}, TT_{ij})$ is the conditional probability of a firm located in i to select transport mode m in the choice set \mathcal{C}_{ij} to export to j given transport costs and transit time values t_{ij} and TT_{ij} respectively.

Because the systematic cost component V_{ij}^m does not take into account any variables that are related to the production of variety ω of a given firm in country i , the MNL model in Equation 4.16 holds for every firm located in i with exports to j . A firm's idiosyncratic preference over a specific transport mode to export to j is captured by the random cost component ε_{kij} .

Step 2: maximise production output. Having determined their optimum marginal cost level, firms choose a price, which—given demand—maximises the number of units sold in the destination market j . The optimisation problem of a firm is given by

$$\max_{\{q_{ij}(\omega)\}_{j \in I}} \sum_{j=1}^I q_{ij}(\omega) \left[p_{ij}(\omega) - \frac{w_i}{z_i} \tau_{ij}^m \right] - w_i f_i^e \text{ s.t. } q_{ij}(\omega) = p_{ij}^{-\sigma}(\omega) X_j \alpha_j^m (P_j^m)^{\sigma-1},$$

where $\omega \in \Omega_{ij}^m$. First order conditions imply that optimal pricing for a firm selling to destination j is a constant markup over marginal cost

$$p_{ij}^m(z_i) = \frac{\sigma}{\sigma-1} \frac{w_i}{z_i} \tau_{ij}^m. \quad (4.17)$$

The optimal pricing condition in this model is therefore identical to the optimal pricing condition in the standard Krugman model with the exception of the trade costs component, which is in this case specified to additionally take time costs into account.

Gravity. Conditional on the selected transport mode m , every firm is charging the same

¹⁴Following Ben-Akiva and Lerman (1985), the intuition of the value of μ is as follows: as $\mu \rightarrow 0$, the variance of the distributions approaches infinity and the alternatives are equally likely; as $\mu \rightarrow \infty$, the variance of the utility disturbances approaches zero and the alternatives become deterministic i.e. all information about individual preferences is contained in the systematic utilities.

price, and substituting the price equation 4.17 for p_{ij} in the demand equation 4.7 yields

$$\begin{aligned} X_{ij} &= X_j P_j^{\sigma-1} \prod_{m \in \mathcal{C}_{ij}}^M \left[\frac{\alpha_j^m}{\lambda_{ij}^m} \int_{\omega \in \Omega_i^m} \left(\frac{\sigma}{\sigma-1} \frac{w_i}{z_i} \tau_{ij}^m \right)^{1-\sigma} d\omega \right]^{\alpha_j^m} \\ &= \left(\frac{\sigma}{\sigma-1} \right)^{1-\sigma} \left(\frac{w_i}{z_i} \right)^{1-\sigma} X_j P_j^{\sigma-1} \prod_{m \in \mathcal{C}_{ij}}^M \left[\frac{\alpha_j^m}{\lambda_{ij}^m} (\tau_{ij}^m)^{1-\sigma} N_i^m(f_i^e) \right]^{\alpha_j^m}, \end{aligned}$$

where $N_i^m(f_i^e) \equiv \int_{\omega \in \Omega_i^m} d\omega$ is the mass of firms producing in country i , which choose to export to country j using transport mode m . The equilibrium number of firms¹⁵ involved in the production of manufactured goods in country i is dependent on the level of fixed costs of entry, f_i^e , and given by $N_i(f_i^e) \equiv \sum_{m=1}^M N_i^m(f_i^e)$.

Multiplying the above equation by $N_i(f_i^e)/N_i(f_i^e)$ and denoting the share of firms in i which select transport mode m to export to foreign markets as $\lambda_i^m = N_i^m(f_i^e)/N_i(f_i^e)$ yields

$$X_{ij} = \left(\frac{\sigma}{\sigma-1} \right)^{1-\sigma} \left(\frac{w_i}{z_i} \right)^{1-\sigma} N_i(f_i^e) X_j P_j^{\sigma-1} \prod_{m \in \mathcal{C}_{ij}}^M \left[\frac{\alpha_j^m \lambda_i^m}{\lambda_{ij}^m} (\tau_{ij}^m)^{1-\sigma} \right]^{\alpha_j^m}.$$

The resulting expression $\alpha_j^m \lambda_i^m$ in the product term measures country j 's expenditure on bundle m goods and country i 's production in bundle m goods, which is inversely related to the denominator of this term, given by country j 's expenditure on bundle m goods from i . To see this, I rewrite this expression using the definition of the share of firms specialised in producing $\omega \in \Omega^m$ from above, the definition of bilateral mode-specific expenditure shares in 4.8, and the definition of the Cobb-Douglas shares $\alpha_j^m = X_j^m/X_j$ (see the market clearing condition below)

$$\frac{\alpha_j^m \lambda_i^m}{\lambda_{ij}^m} = \frac{X_j^m}{X_j} \frac{N_i^m(f_i^e)}{N_i(f_i^e)} \frac{X_{ij}}{X_{ij}^m}.$$

Because country j 's spending on goods imported from i , X_{ij} , is determined by country j 's total expenditure X_j and the number of products produced in country i , $N_i(f_i^e)$, no explicit solution to the term $\alpha_j^m \lambda_i^m / \lambda_{ij}^m$ exists. I therefore chose to evaluate the gravity equation at a point of symmetry where $\frac{\alpha_j^m \lambda_i^m}{\lambda_{ij}^m} \equiv \text{constant}$.

The final model *for estimation* can then be written as (using 4.11)

$$X_{ij} = \left(\frac{\sigma}{\sigma-1} \right)^{1-\sigma} \left(\frac{w_i}{z_i} \right)^{1-\sigma} N_i(f_i^e) X_j P_j^{\sigma-1} \prod_{m \in \mathcal{C}_{ij}}^M \left(1 + \frac{t_{ij}^m + s_{ij}^m}{w_i/z_i} \right)^{(1-\sigma)\alpha_j^m}, \quad (4.18)$$

¹⁵Fixed exporting costs f_i^e are specified independent of transport and time costs. For this reason, it is not necessary to determine the equilibrium number of firms in this model.

with mode choices given by (using 4.16)

$$\mathbb{P}_{ij} (m \in \mathcal{C}_{ij}) = \frac{\exp [\mu\beta_0^m + \mu\beta_3^m (t_{ij}^m + VOT^m \cdot TT_{ij}^m)]}{\sum_{m \in \mathcal{C}_{ij}}^M \exp [\mu\beta_0^k + \mu\beta_3^k (t_{ij}^k + VOT^k \cdot TT_{ij}^k)]}.$$

Equation 4.18 is what I will refer to as gravity equation in this model, consisting of an exporter term (i), an importer term (j) and a bilateral transport costs term (ij). With $\sigma > 1$ and conditional on the selected transport mode, Equation 4.18 implies that bilateral trade flows X_{ij} are

- decreasing with wage w_i in country i as higher wage results into higher production costs and thus prices $p_{ij}^m(z_i)$ (see Equation 4.17),
- increasing with productivity z_i as higher productivity lowers the cost of production,
- increasing with the equilibrium number of firms N_i exporting to country j as each firm produces a unique variety and consumers would like to consume at least a little of each variety (more firms therefore results into more goods imported by j),
- increasing with country j 's expenditure X_j ,
- increasing with j 's price index P_j as goods imported from country i are becoming relatively cheaper if P_j increases, and
- decreasing with increasing transport costs t_{ij}^m or time costs s_{ij}^m respectively.

Because 4.18 predicts aggregate bilateral flows X_{ij} of all varieties produced in i and exported to j using all available transport modes $m \in \mathcal{C}_{ij}$, it is possible to also specify an aggregate measure of τ_{ij} . To do so, I first transform Equation 4.18 into its logarithmic form

$$\ln X_{ij} = \delta_i + \delta_j + (1 - \sigma) \overbrace{\sum_{m \in \mathcal{C}_{ij}}^M \alpha_j^m \ln \left(1 + \underbrace{\frac{t_{ij}^m + s_{ij}^m}{w_i/z_i}}_{\tau_{ij}^m} \right)}^{\ln \tau_{ij}} \quad (4.19)$$

where I used $\delta_i = (1 - \sigma) \ln \left(\frac{w_i}{z_i} \right) + \ln N_i(f_i^e)$ for the exporter fixed effect and $\delta_j = \ln X_j - (1 - \sigma) \ln P_j$ for the importer fixed effect. This transformation is possible as all the variables entering 4.18 can be grouped into i , j or ij terms, thereby remaining multiplicatively separable¹⁶. From Equation 4.19 it can be seen that the log of τ_{ij} essentially represents an aggregated measure of the log of mode specific ad valorem transport costs τ_{ij}^m where each individual mode-specific term is weighted by the Cobb-Douglas share α_j^m , mathematically: $\ln \tau_{ij} \equiv \sum_{m \in \mathcal{C}_{ij}}^M \alpha_j^m \ln \tau_{ij}^m$.

Given these observations, the partial elasticity of relative imports with respect to overall

¹⁶Equation 4.18 therefore satisfies the separability condition of gravity equations (Head and Mayer, 2014, Fally, 2015).

transport costs can be defined as¹⁷

$$1 - \sigma = \frac{\partial \ln (X_{ij}/X_{jj})}{\partial \sum_{m \in \mathcal{C}_{ij}}^M \alpha_j^m \ln [1 + (t_{ij}^m + s_{ij}^m) / (w_i/z_i)]} = \frac{\partial \ln (X_{ij}/X_{jj})}{\partial \sum_{m \in \mathcal{C}_{ij}}^M \alpha_j^m \ln \tau_{ij}^m} \quad (4.20)$$

where X_{jj} is the value of goods produced and also consumed in country j .

Market clearing. To the close the model, I impose the following market clearing condition

$$w_i L_i \equiv \sum_{j=1}^I X_{ij}. \quad (4.21)$$

That is, i 's production value $w_i L_i$ *inclusive* of transport costs is equivalent to the sum of i 's exports to all destinations j , including i 's export to its own home market X_{ii} .

On the demand side, country j 's expenditure must be equivalent to the sum of j 's imports from all supply countries i , including j 's imports from its own home market X_{jj}

$$X_j \equiv \sum_{i=1}^I X_{ij} = \sum_{m=1}^M X_j^m = \sum_{m=1}^M \sum_{i=1}^I X_{ij}^m. \quad (4.22)$$

It follows that country j 's overall expenditure share on the bundle of m goods α_j^m and overall, bilateral budget shares λ_{ij} are given by

$$\alpha_j^m \equiv \frac{X_j^m}{X_j}, \quad (4.23)$$

$$\lambda_{ij} \equiv \frac{X_{ij}}{X_j} = \frac{X_{ij}}{\sum_{i=1}^I X_{ij}}. \quad (4.24)$$

To comply with structural gravity, bilateral budget shares must remain multiplicatively separable (Head and Mayer, 2014). In other words, λ_{ij} must remain independent of country j 's income $w_j L_j$. This can be shown by substituting trade flows for the gravity equation in 4.18 to obtain

$$\lambda_{ij} = \frac{\left(\frac{w_i}{z_i}\right)^{1-\sigma} N_i(f_i^e) \prod_{m \in \mathcal{C}_{ij}}^M (\tau_{ij}^m)^{(1-\sigma)\alpha_j^m}}{\sum_{i=1}^I \left(\frac{w_i}{z_i}\right)^{1-\sigma} N_i(f_i^e) \prod_{m \in \mathcal{C}_{ij}}^M (\tau_{ij}^m)^{(1-\sigma)\alpha_j^m}}. \quad (4.25)$$

Similarly, using Equation 4.5, substituting $p_{ij}(\omega \in \Omega^m)$ for the optimal price equation 4.17, and integrating over all varieties $\omega \in \Omega^m$ yields into a gravity equation for mode-specific

¹⁷If the elasticity of substitution between the goods $\omega \in \Omega^m$ is assumed to also vary by transport mode m , the partial elasticity of relative imports with respect to mode-specific transport would be given by

$$1 - \sigma^m = \frac{\partial \ln (X_{ij}/X_{jj})}{\partial \ln [1 + (t_{ij}^m + s_{ij}^m) / (w_i/z_i)]} = \frac{\partial \ln (X_{ij}/X_{jj})}{\partial \ln \tau_{ij}^m} \quad \forall m \in M.$$

bilateral trade flows

$$X_{ij}^m = \left(\frac{\sigma}{\sigma - 1} \right)^{1-\sigma} \left(\frac{w_i}{z_i} \right)^{1-\sigma} N_i^m(f_i^e) X_j \alpha_j^m (P_j^m)^{\sigma-1} (\tau_{ij}^m)^{(1-\sigma)} \quad (4.26)$$

Using this expression in the definition for λ_{ij}^m , I immediately obtain

$$\lambda_{ij}^m = \frac{X_{ij}^m}{\sum_{m \in \mathcal{C}_{ij}} X_{ij}^m} = \frac{N_i^m(f_i^e) \alpha_j^m (\tau_{ij}^m)^{1-\sigma}}{\sum_{m \in \mathcal{C}_{ij}} N_i^m(f_i^e) \alpha_j^m (\tau_{ij}^m)^{1-\sigma}}, \quad (4.27)$$

which is the proof of Proposition 1.

Country j 's budget shares, λ_{ij} and λ_{ij}^m , are therefore both independent of country j 's labour endowment and therefore ensure multiplicative separability, while α_j^m is a predetermined structural model parameter of the Cobb-Douglas demand function.

Jointly, Equations 4.24 and 4.25 as well as Equations 4.8 and 4.27 ensure that budget shares sum to one

$$\sum_{i=1}^I \lambda_{ij} = \sum_{i=1}^I \frac{X_{ij}}{\sum_{i=1}^I X_{ij}} = 1, \quad \sum_{m=1}^M \lambda_{ij}^m = \sum_{m=1}^M \frac{X_{ij}^m}{\sum_{m=1}^M X_{ij}^m} = 1, \quad (4.28)$$

which completes my description of the trade equilibrium in this economy.

Model isomorphism. It is easily verified that the theoretical model outlined in this section is isomorphic to the Krugman (1980) model with monopolistic competition and increasing returns to scale. Assume that all transport modes exhibit the same transport costs and transit time values. The need to distinguish between transport modes is therefore superfluous and the budget share for a consumer to consume the only available bundle $\omega \in \Omega$ is equal to one ($\alpha_j = 1$). On the production side, country i now also focuses only on producing goods that are commonly exported using m as the only available transport mode ($\lambda_i^m = 1$). As a result, country j 's bilateral expenditure share on the bundle of goods imported from country i is also equal to one ($\lambda_{ij}^m = 1$). Combining these observations in Equation 4.18 gives

$$X_{ij} = \left(\frac{\sigma}{\sigma - 1} \right)^{1-\sigma} \left(\frac{w_i}{z_i} \right)^{1-\sigma} N_i(f_i^e) X_j P_j^{\sigma-1}, \tau_{ij}^{1-\sigma} \quad (4.29)$$

which is the standard gravity equation in theoretical models with many firms in one country, each of which produces a unique variety and operates in a monopolistic market.

The model could also be taken to the Chaney-Melitz model of monopolistic competition with CES (Chaney, 2008, Melitz, 2003) to account for exporting decisions of firms with respect to fixed exporting costs f_{ij} (see e.g. Helpman, Melitz and Rubinstein, 2008). The homogeneous good as specified in Chaney (2008), which is freely traded and thus implies

$t_{ij}^0 \equiv 0$ as well as $TT_{ij}^0 \equiv 0$ and therefore $V_{ij}^0 \equiv 0$ and $\exp(\mu V_{ij}^0) = 1$, adds the outside alternative of not choosing any transport mode to the MNL model in Equation 4.16. The use of an homogeneous good can also be found in empirical studies of differentiated product markets, where an outside alternative is added to represent the option of not purchasing any of the products available to the consumer (e.g. Berry, Levinsohn and Pakes, 1995). On the demand side, fixed exporting costs f_{ij} , which now vary bilaterally, determine a firm's selection into exporting to j . Average prices charged by all firms therefore become dependent on the average productivity of the equilibrium number of firms who chose to export to j , which changes Equation 4.17. Together, changes in Equations 4.16 and 4.17 provide the theoretical basis to develop a Chaney-Melitz version of the model presented in this section.

Limitations. Because transport prices and transit time vary by country pair, a firm in country i exporting to destination j using mode m might consider a different mode of transport, $k \neq m$, in shipping the same produced variety to another destination, say l . This is because transport costs, $t_{ij}^m \neq t_{il}^m$, and transit times, $TT_{ij}^m \neq TT_{il}^m$ vary by trade routes and thus country pairs. While Equation 4.16 does in principal account for this firm behaviour on the supply side, the theoretical framework on the demand side remains restrictive to one variety and one characteristic transport mode only. From the very beginning, I assumed that varieties can be grouped into bundles $\omega \in \Omega_i^m$, where $\Omega_i^m \subset \Omega_i$. For a model to reflect bilateral variations in transport modes for each variety, the varieties must be bundled using $\omega \in \Omega_{ij}^m$, where $\Omega_{ij}^m \subset \Omega_i^m \subset \Omega_i$. The number of varieties produced in country i would therefore also become dependent on the destination market: $\int_{\omega \in \Omega_{ij}^m} d\omega = N_{ij}^m(f_i^e)$. Keeping track of the number of varieties produced, which reflect certain characteristics to be shipped to j using multiple transport modes, remains however difficult in an international trade setting, as not only multiple countries must be dealt with but also multiple types of bundles, both of which vary by country pairs.

The way to think about multiple transport modes by destination country in the model described above is as follows. If the firm is using multiple transport modes, then it is intuitively appealing to think of those goods as two distinct varieties. As multiproduct firms are however not accounted for in the model, a firm producing two varieties is thought of as representing two separate firms, each producing a unique variety and using one characteristic transport mode.

4.3 Data

To estimate the key parameters of the model, I use bilateral trade data from Eurostat (2014). The dataset contains bilateral trade flows by mode of transport with a reporting threshold of 1.000 € in value over a 2001-13 time period between any EU country and any

non-EU country (see Appendix A.1 for a description of the data).

Extra-EU trade data by mode of transport has not been used extensively in the literature, predominantly due to its limited coverage¹⁸ and missing flows¹⁹. Given the focus of this study on bilateral trade by mode of transport however, these limitations are unavoidable and the results of this study are therefore limited to EU member countries only.

In Appendix A.1, I investigate the extra-EU trade dataset with respect to mode-specific differences in value-to-weight ratios and product groups. For some observations I find that the reported means of transport does not reflect the primary means of transport that is used to bridge the greatest distance (e.g. EU imports from the US using road transport). In such cases, I adjust the transport mode manually and assume sea transport as the default mode. In the corrected dataset, trade by surface transport (rail, road, etc.) only occurs between countries which are on the same landmass.

Because the transport between countries which are not on the same landmass is restricted to air and sea transport only, the choice set $\mathcal{C}_{ij} \subset M$ varies by country pair (ij) . As the log odds ratio (see below) prohibits the inclusion of zero flows in the estimation, the choice set needs to be constrained to the alternatives that are common to each country pair. If all available transport modes are considered, the sample size reduces considerably and only includes trade between nearby or neighbouring countries²⁰ (see Figure A.1). I therefore restrict M to the frequently considered transport modes sea and air. The final dataset does therefore not contain any bilateral flows other than trade by air and sea.

Because transport costs and transit time values are not reported, I rely on external data sources to complement the extra-EU dataset with transport cost and transit time variables. In both cases, I estimate a functional form that allows to approximate transport costs and transit time values using prices, quantities and distances. Within certain limits, these approximations are acceptable for estimating a MNL model as only differences in systematic utility (or costs) matter in a choice situation (see Equation 4.14). Given the large differences in time and cost of air versus sea transport, neither the transport cost nor the transit time variable need to be exact in absolute levels to obtain an approximation of the value of time.

In Appendix A.2, I describe the method I use to estimate bilateral transit time dependent

¹⁸Lux (2011) therefore combines extra-EU trade data with extra-US trade data (North American Transborder Freight Data); Martinez, Kauppila and Gachassin (2014) combine extra-EU trade with Latin America-extra trade (Base de datos de Transporte Internacional, BTI).

¹⁹Reported are imports into the EU and exports from the EU. The pendant to either flow is not included in the data.

²⁰Considering all available transport modes in M would require to exclude all country pairs, which utilise less than the available transport alternatives defined in M , from the dataset for estimation. In this case, the sample would only include trade, which occurs over short distances as the surface transport modes (foremost rail and road) are included as alternatives. In addition, the data does not include intra-EU trade, imposing further constraints on the sample.

on bilateral distance and average transport speed. To be compliant with the annual reporting of trade data, I approximate transit time values using *average* trip speeds, which I assume to be representative for the reporting period of an entire year. The method uses a power function to describe the relationship between average trip speed and average trip distance²¹. Because no further information on operational transport patterns is available, the calculated transit time values for a given country pair remain identical over each time period.

In the text below, I explain the method I use to model transport costs.

I adopt the empirical specification of Hummels and Skiba (2004) and write freight rates f as a log-linear function of observable, nonprice portions of freight charges

$$\ln f_{ij} = \beta_0 + \beta_1 \ln \left(\underbrace{\frac{X_{ij}}{q_{ij}}}_{w_i/z_i} - t_{ij} \right) + \beta_2 \ln q_{ij} + \beta_3 \ln D_{ij} + \varepsilon_{ij}, \quad (4.30)$$

where t are per unit freight charges (in \$/kg), w_i/z_i is the goods' price (exclusive of freight costs) at the factory gate, q is the total shipment quantity (in kg), and D is country pair distance (in km). The error term captures any unobserved cost shifters and measurement errors.

I estimate this equation for air and ocean freight rates using data from the OECD Maritime Transport Cost database (OECD, 2007) for containerized seaborne trade and data from Hummels (2007) for airborne trade. Table 4.1 contains the results.

Table 4.1: Approximation of transport costs.

(1) Variables (in logs)	(2) Ocean freight rate	(3) Ocean freight rate	(4) Air freight rate	(5) Air freight rate
Price [\$/kg]	0.543 (0.004)	0.541 (0.005)	0.386 (0.001)	0.320 (0.001)
Quantity [kg]	-0.042 (0.001)	-0.059 (0.002)	-0.089 (0.000)	-0.121 (0.000)
Distance [km]	0.178 (0.007)	0.125 (0.008)	—	—
Constant [-]	-3.480 (0.069)	-2.180 (0.118)	0.050 (0.004)	-0.420 (0.146)
Fixed effects [-]	no	yes	no	yes
Observations	17,941	17,941	893,772	893,085
R ²	0.62	0.70	0.44	0.57

Notes: Estimated is Equation 4.30 using ordinary least squares (OLS) and the log of air or ocean freight rates in [\$/kg] as dependent variable. For the total of containerized manufacturing seaborne trade, the fixed effects are specified for each origin country, destination country and year; for airborne trade by commodity group, the fixed effects are specified for each destination country, commodity group, and year. Standard errors are in parentheses.

The elasticities of freight rates with respect to prices at the factory gate obtain a significant positive value of 0.54 for seaborne trade and 0.32 for airborne trade and implicate the following two conclusions. First conjectured by Alchian and Allen (1967) and documented by Hummels and Skiba (2004), because freight costs are increasing with the price of the

²¹Because of operational inefficiencies, the average trip speed is declining with decreasing average trip distance. See Appendix A.2.

good, firms tend to sell goods with higher unit values in foreign markets (exports), while selling goods with lower unit values in the domestic or home market. In other words, because transport costs associated with exporting would take up a significant share of the overall price of goods with lower unit values, they are rarely sold in foreign markets. The significantly smaller elasticity for airborne trade indicates that transport costs are lower relative to the goods' prices as a result of a significantly large share of goods with higher unit values imported by air. Second, because the price elasticity is in all cases not equal to one, transport costs are not purely ad valorem to the price at the factory gate and the iceberg assumption in Equation 4.11 should therefore be rejected (Hummels and Skiba, 2004). Measuring the price elasticity of demand $1 - \sigma$ from iceberg transport costs therefore inevitably involves some levels of inaccuracy, which are amplifying with increasing per unit costs of the exported goods.

The elasticities of freight rates with respect to quantity are all negative, indicating that the per unit costs are falling in shipment size due to transport economies of scale. Because the data for airborne trade is by importing country only, a country pair distance variable cannot be included in the regression.

To control for any location and time specific variation in those results (e.g. local port and bunker fuel prices and their variation over time), I include importer, exporter and year fixed effects (columns 3 and 5 in Table 4.1), which changes the coefficient estimates only marginally. Because prices at the factory gate may be determined simultaneously with freight rates, they are endogenous. The results in Hummels and Skiba (2004) however indicate that this endogeneity issue is less of a problem.

I use the coefficient estimates in columns 3 and 4²² in Table 4.1 to calculate the transport costs of seaborne and airborne manufacturing trade in the extra-EU trade dataset by mode of transport for all commodity groups²³. I assume that any price variations not captured by the variables in Equation 4.30 are absorbed by a constant marginal cost term (AP), which I add to the side of manufacturing exports by air

$$t_{ij}^s \equiv f_{ij}^s = e^{\hat{\beta}_0^s} (w_i^s / z_i^s)^{\hat{\beta}_1^s} (q_{ij}^s)^{\hat{\beta}_2^s} (D_{ij}^s)^{\hat{\beta}_3^s} \quad (4.31)$$

$$t_{ij}^a \equiv f_{ij}^a + AP = e^{\hat{\beta}_0^a} (w_i^a / z_i^a)^{\hat{\beta}_1^a} (q_{ij}^a)^{\hat{\beta}_2^a} + AP. \quad (4.32)$$

Because AP is representative of a marginal transport markup that is added to the marginal freight costs part f_{ij}^a , I refer to it as being the air premium that firms face when choosing

²² $\hat{\beta}_0^a$ is not significant in column 5. Using the coefficient estimates in column 4, I obtain a medium value of air freight rates that is closer to the reported air freight rates.

²³ The price variable controls for any variation in the per unit value of the traded good. I therefore apply the coefficients in Table 4.1 to all disaggregated product levels (see Appendix A.1 for a description of the commodity groups). I calculate w_i/z_i for exports using the reported FOB values. As extra-EU trade data does not include FOB values for imports, I approximate w_i/z_i for imports using the reported CIF values and include a binary variable for imports in the MNL estimation. I do not report the coefficient estimates of this variable in the results section.

air over sea transport. The value of the air premium (in units of [\$/kg]) will be recovered from the alternative specific constant in the MNL estimation below.

In Appendix A.1 I investigate freight rates of seaborne trade using data from the OECD and find that, on average, the transport of manufactured goods accounts for 6% of the traded value, corresponding to a freight rate of about $t^{\text{sea}} = 0.26$ \$/kg. Using the coefficient estimates in Table 4.1 and extra-EU trade data by mode of transport, I obtain a median ocean freight rate of $t^{\text{sea}} = 0.27$ \$/kg and a median air freight rate of $t^{\text{air}} = 2.04$ \$/kg (assuming $1\$ \approx 1\text{€}$), both of which are well in line with actual reported values (Table A.2 and UPS, 2016). Ultimately, the predicted values of transport costs by mode of transport are however a first order approximation under limited information, as the functional form does not account for any local (or country specific) variation in transport costs.

In the next section, I use the differences in transport costs and transit time values by mode of transport to estimate the MNL model of transport mode choice in international trade.

4.4 Trade and mode-specific preferences

Motivated by the theoretical model outlined above, this section deals with the estimation of cost and time parameters of firms choosing different transport modes for exporting. Of particular interest is in this respect the estimation of the VOT, which—in combination with transit time values—provide insight into the significance of time costs in international trade.

Recalling from Equation 4.16, a firm's decision to export to j using transport mode m can be described as

$$\mathbb{P}_{ij}(m \in \mathcal{C}_{ij} | t_{ij}, TT_{ij}) = \frac{e^{\mu V_{ij}^m}}{\sum_{m \in \mathcal{C}_{ij}}^M e^{\mu V_{ij}^m}},$$

where $\mathbb{P}_{ij}(m \in \mathcal{C}_{ij})$ is the probability of a firm located in i to choose m to export to j . Estimating this equation would in practice be straightforward if revealed preference data of firms were available. In the case of international trade data however, the information of firms choosing transport mode m to export to j is only available in aggregated form²⁴. It is therefore necessary to first transform the MNL model into a nonlinear probability model before I can proceed with the estimation of the VOT. First shown by Berkson (1953) and extended by Theil (1969), this transformation requires the systematic cost function V to be linear in its parameters and the choice probabilities to be independent from irrelevant alternatives.

As described earlier in the theoretical framework, the systematic component of the marginal

²⁴several firms choosing m to export to j to ship quantities q_{ij}^m

cost function of a firm is given by $V_{ij}^m = \beta_0^m + \beta_3^m (t_{ij}^m + VOT^m \cdot TT_{ij}^m)$, which is a linear in the parameters utility function. Denoting $\boldsymbol{\beta} = [\beta_0^m, \beta_2^m, \dots, \beta_0^k, \beta_2^k, \dots, \beta_A^k]$ as the vector of A unknown parameters of all alternatives k that are common to all firms and $\mathbf{x}_{ij}^m = [TT_{ij}^m, t_{ij}^m]$ as the vector of attributes characterising the firm as a decision maker, the restricted (linear-in-parameters) version of the MNL model can be written as

$$\mathbb{P}_{ij}(m) = \frac{e^{\mu \boldsymbol{\beta}' \mathbf{x}_{ij}^m}}{\sum_{m \in \mathcal{C}_{ij}} e^{\mu \boldsymbol{\beta}' \mathbf{x}_{ij}^m}}.$$

The IIA property states that the disturbances are mutually independent (Ben-Akiva and Lerman, 1985), such that

$$\frac{\mathbb{P}_{ij}(m)}{\mathbb{P}_{ij}(l)} = \frac{e^{\mu V_{ij}^m} / \sum_{m \in \mathcal{C}_{ij}} e^{\mu V_{ij}^m}}{e^{\mu V_{ij}^l} / \sum_{m \in \mathcal{C}_{ij}} e^{\mu V_{ij}^m}} = e^{\mu(V_{ij}^m - V_{ij}^l)} \quad (\forall m \neq l, \{m, l\} \in \mathcal{C}_{ij}).$$

In terms of the prevailing model, the IIA property essentially means that the ratio of the choice probabilities (the odds ratio) of any two transport alternatives of a representative firm in country i is entirely unaffected by the systematic cost of any other transport alternative. Given the differences in the systematic cost components, firms therefore choose e.g. sea transport over air transport in a specific choice situation, irrespective of the fact that e.g. road transport is also available or not available to them²⁵.

Jointly, the linear-in-parameters and IIA property yield

$$\frac{\mathbb{P}_{ij}(m)}{\mathbb{P}_{ij}(l)} = \exp \left[\mu \boldsymbol{\beta}' (\mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l) \right] \quad (\forall m \neq l, \{m, l\} \in \mathcal{C}_{ij}).$$

To arrive at the nonlinear probability model, I consider $N_i^m(f_i^e)$ firms, located in country i , where each individual firm is responsible for shipping quantity q_{ij}^m goods from i to j using transport mode m . I assume that this group of firms can be divided into $G < N$ homogeneous subgroups of size $N_{i1}^m, N_{i2}^m, N_{i3}^m, \dots, N_{iG}^m$, where $\sum_{g=1}^G N_{ig}^m = N_i^m(f_i^e)$. If each of those subgroups is homogeneous in terms of $\mathbf{x}_{ij} = \mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l$ (Ben-Akiva and Lerman, 1985), then, by Berkson's method, the ratio of the choice probabilities of any two alternatives can be estimated using the share of each subgroup in shipping quantities q_{igj}^m and q_{igj}^l to j

$$\ln \left(\frac{q_{igj}^m / q_{igj}}{q_{igj}^l / q_{igj}} \right) = \mu \boldsymbol{\beta}' (\mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l)_g + \varsigma_{igj} \quad (\forall m \neq l, \{m, l\} \in \mathcal{C}_{ij}), \quad (4.33)$$

with $q_{igj} \equiv \sum_{m \in \mathcal{C}_{ij}} q_{igj}^m$ and where ς is a heteroskedastic error term (Cox and Snell, 1989) as a result of the logarithmic transformation.

²⁵The IIA property fails if the disturbances between alternatives are correlated, that is, if the alternatives are close substitutes. In such cases, a nested logit model is preferred over the simple logit model.

As trade data by mode of transport is however only available in aggregated form by country pairs, only $G = ij \times m = N$ subgroups can be formed, which thus implies having as many subgroups as observations and $G < N$ cannot be satisfied. This leaves two options: decrease G or increase N . The first option would imply to treat multiple ij^m observations as one group (g) which would however contradict the gravity setting in treating each country's supply capacity and market demand individually. The second option, which is my preferred option, is to increase N by observations at different points in time t , so as to obtain multiple observations per mode of transport for the same country pair $G < N \cdot (t_e - t_s)$, where t_s is the start year and t_e the end year. This approach solves the issue of forming subgroups under limited information while ensuring that these subgroups are also homogeneous in terms of $\mathbf{x}_{ij} = \mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l$. This is because a firm's decision to export to j using m is influenced by economic or geographical aspects related to country i or country j respectively. A subgroup specified for each time period therefore still refers to the same country pair, thus preserving any long-run i or j specific conditions (e.g. local port charges), while any short-run variations (e.g. a year-over-year change in local prices) are captured by the time series component.

In treating the subgroups as individual country pair observations over time, the group index g can be substituted with a time index t

$$\ln \left(\frac{q_{ij}^m}{q_{ij}^l} \right)_t = \mu \boldsymbol{\beta}' (\mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l)_t + \varsigma_{ijt} \quad (\forall m \neq l, \{m, l\} \in \mathcal{C}_{ij}), \quad (4.34)$$

where the choice set \mathcal{C}_{ij} must remain identical over all time periods.

Equation 4.34 can be used to estimate the unknown parameters $\boldsymbol{\beta}$, including the VOT, using bilateral trade data by mode of transport, which has been collected over several time periods.

Because the subgroups of the nonlinear probability model are formed as repeated observations over time, I account for autocorrelation in variables by adding a lagged mode share $(q_{ij}^m/q_{ij})_{t-1}$ to the systematic cost component V_{ij}^m to obtain

$$(\boldsymbol{\beta}' \mathbf{x}_{ij}^m)_t = \beta_0^m + \beta_1 \ln (q_{ij}^m/q_{ij})_{t-1} + \beta_3^m (t_{ij}^m + VOT^m \cdot TT_{ij}^m)_t. \quad (4.35)$$

For any given country pair, the nonlinear probability model therefore takes the form of an autoregressive model.

As Schäfer (2015) notes, in the context of a respondent's systematic utility, the lagged mode share represents the constraint of a respondent (e.g. a firm) in choosing mode m under limited information and with respect to the potential influence of habits on these decisions. The mode choice at time t is thus partially also determined by its preceding mode choice at time $t - 1$. The lagged mode share therefore measures the inertia associated with choosing

the same mode m within two consecutive time-steps. In the prevailing case above however, β_1 is specified as a parameter common to all country pairs in the cross-section and therefore represents the *average* predetermined preference within two consecutive time-steps *across* all country pairs in the sample. Its informative value is therefore limited.

Substituting $\beta'(\mathbf{x}_{ij}^m)_t$ in Equation 4.34 with the systematic component of the marginal cost function given by 4.35, 4.31 and 4.32, and choosing sea transport as the reference transport mode²⁶ l yields into the following system of equations

$$\begin{aligned}
\ln\left(\frac{q_{ij}^a}{q_{ij}^s}\right)_t &= \mu\beta_0^a + \mu\beta_1 \ln\left(\frac{q_{ij}^a}{q_{ij}^s}\right)_{t-1} + \mu\beta_2^a TT_{ijt}^a - \mu\beta_2^s TT_{ijt}^s + \\
&\quad \mu\beta_3^a (f_{ijt}^a + AP) - \mu\beta_3^s f_{ijt}^s + \varsigma_{ijt} \\
\ln\left(\frac{q_{ij}^r}{q_{ij}^s}\right)_t &= \mu\beta_0^r + \mu\beta_1 \ln\left(\frac{q_{ij}^r}{q_{ij}^s}\right)_{t-1} + \mu\beta_2^r TT_{ijt}^r - \mu\beta_2^s TT_{ijt}^s + \\
&\quad \mu\beta_3^r f_{ijt}^r - \mu\beta_3^s f_{ijt}^s + \varsigma_{ijt} \\
&\vdots \\
\ln\left(\frac{q_{ij}^m}{q_{ij}^s}\right)_t &= \mu\beta_0^m + \dots,
\end{aligned} \tag{4.36}$$

where the transport modes $m \in \mathcal{C}_{ij}$ for a firm located in i to export to j are indicated using s for sea, a for air, and r for road transport (to name a few). Assuming that each good produced in i and exported to j weighs one tonne, q_{ij} can be measured by the total tonnes imported from i using transport mode m . TT refers to the transit time in [h], f to the freight rate in [€/kg], and AP to the air premium in [€/kg] (see Equation 4.32). Note that the alternative-specific constants β_0 , the time coefficients β_2 , as well as the cost coefficients β_3 , are specified separately for each transport alternative, while β_1 is a parameter assumed to be common to all alternatives.

The optimisation conditions of a representative firm and the parameters β imply that the disturbances among the odds ratios in Equation 4.36 should be correlated and therefore be estimated jointly, using a seemingly unrelated regression (Greene, 2002). In an ideal case therefore, Equation 4.36 is estimated using an exhaustive choice set $\mathcal{C}_{ij} \subset M$ that consists of all mutually exclusive alternatives $m \in \mathcal{C}_{ij}$. For reasons of sufficient sample size however (see Section 4.3 above), the choice is constraint to the alternatives $M \equiv \{\text{sea, air}\}$ for all country pairs. This is a reasonable simplification as the choice parameters can also be estimated consistently on a subset of alternatives if the IIA property holds (Train, 2009).

I estimate the air to sea odds ratio of 4.36 (top line) using non-linear least squares. I calculate the variables of the systematic cost component of a firm using (i) reported extra-EU trade quantities by mode of transport for q_{ijt}^m , (ii) reported extra-EU trade values and

²⁶The choice of the reference mode is arbitrary.

quantities and the coefficient estimates in Table 4.1 for t_{ijt}^m , and (iii) bilateral distances and the coefficient estimates in Figures A.3 and A.4 for TT_{ijt}^m . To recover the value of the air premium AP , I first estimate 4.36 using the restriction $\mu\beta_0^a = \mu ASC + \mu\beta_3^a AP \equiv \mu\beta_3^a AP$, where ASC is the alternative specific constant. In this case, μASC remains as the only estimated constant in the model. I then estimate the same equation without restrictions to obtain a value of $\mu\beta_0^a$. The value of the AP can then be calculated using $AP = (\mu\beta_0^a - \mu ASC)/\mu\beta_3^a$. Table 4.2 contains the results.

In all regressions, the ASC (column 3) obtains a negative value, indicating a relative preference for sea transport, holding transport and time costs fixed. Except for coke and petroleum products²⁷, the absolute value of the ASC indicates that the various elements in \mathbf{x} form a systematic cost function V that captures the relevant differences in attributes between alternatives. V therefore responds well to the established theory about transport choice in an international trade context. A relatively high absolute value of the ASC would indicate omitted-variable bias (OVB). Restricting a firm's decision of choosing a transport mode exclusively to the attributes of cost and time evidently omits other potential influences on these choice situations including insurance, loss and damage, delivery time, and reliability. If these attributes were measurable and included in the systematic cost component²⁸, an even lower value of the ASC could potentially be obtained.

The air premium (column 4) is positive and significant for all commodity groups and ranges from 0.6 €/kg for textiles to 20 €/kg for minerals, with a central estimate of 2.7 €/kg for the total of manufacturing goods. A high value of the AP reflects the additional costs (special packaging and handling, insurance) associated with transporting hazardous goods (e.g. chemicals), time and temperature sensitive goods (pharmaceuticals), fragile goods (e.g. pottery in non-metallic mineral products) or valuable goods (e.g. minerals in non-metallic mineral products). For all other commodity groups, the AP remains relatively low in value, as the systematic cost differences are mainly captured by the differences in variables of transport cost and transit time.

The preference of firms to choose either sea or air transport to export to foreign countries is largely pre-determined. On average, almost 70 % of relative mode preference is pre-determined between two consecutive years (column 5), leaving 30 % of relative preference to be chosen freely at any time step. The estimated coefficients are however averaged across the time series and cross-sectional component of the dataset and therefore representative for all country pairs in the dataset. A relatively lower value of this estimate therefore indicates volatility of the quantities commonly shipped via air against sea transport between countries i and j . Significant changes in the quantities shipped in the data are a result of

²⁷ Also includes other non-fuel petroleum derivatives.

²⁸ Ideally, the various elements in \mathbf{x} form a systematic cost function V that responds to any theory about transport choice, thereby capturing relevant differences in attributes between alternatives. In practice however, \mathbf{x} can only take into account attributes that are observable and measurable, while V must be specified in way to remain computational.

Table 4.2: The value of time in international trade

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
#	Industry	ASC air μASC^a	AP AP	Habit c. $\mu \beta_1$	Sea transport Time c. $\mu \beta_2^s$	Cost c. $\mu \beta_3^s$	VOT β_2^s / β_3^s	Air transport Time c. $\mu \beta_2^a$	Cost c. $\mu \beta_3^a$	VOT β_2^a / β_3^a	N	R ²
		[-]	[€/kg]	[-]	[h]	[€/kg]	[€/t/h]	[h]	[€/kg]	[€/t/h]	[-]	[-]
9-24	Manufacturing	-1.070 (-56.72)	2.702 (24.44)	0.688 (209.16)	-0.000577 (-16.41)	-2.151 (-55.38)	0.268 (15.53)	-0.019756 (-8.23)	-0.396 (-61.51)	49.870 (8.17)	32,876	0.74
9	Food products	-0.961 (-29.83)	0.881 (14.12)	0.636 (113.98)	-0.000194 (-3.19)	-5.572 (-35.04)	0.035 (3.17)	-0.032066 (-7.41)	-1.091 (-55.43)	29.387 (7.39)	10,750	0.73
10	Beverages	-1.204 (-16.85)	1.341 (7.63)	0.554 (48.90)	-0.000767 (-6.25)	-1.614 (-17.29)	0.475 (5.92)	-0.065320 (-7.92)	-0.898 (-27.83)	72.749 (7.66)	3,615	0.57
11	Tobacco products	-0.357 (-1.64)	0.737 (0.75)	0.729 (20.82)	0.000015 (0.03)	-0.622 (-6.13)	-0.024 (-0.03)	0.044641 (1.07)	-0.484 (-3.96)	-92.138 (-1.09)	289	0.74
12	Textiles	-0.493 (-19.97)	0.613 (9.18)	0.645 (129.37)	0.000177 (4.19)	-1.694 (-45.66)	-0.105 (-4.24)	0.008255 (2.80)	-0.805 (-51.67)	-10.254 (-2.81)	14,046	0.72
13	Wearing apparel & leather	-0.351 (-18.04)	0.692 (8.41)	0.711 (164.62)	0.000083 (1.98)	-0.849 (-47.50)	-0.098 (-1.99)	-0.002756 (-0.93)	-0.507 (-44.51)	5.435 (0.93)	16,365	0.72
14	Wood & cork products	-0.882 (-19.97)	0.681 (9.25)	0.561 (75.51)	0.000297 (4.00)	-4.598 (-40.29)	-0.065 (-3.98)	-0.006214 (-1.12)	-1.295 (-48.29)	4.799 (1.12)	6,350	0.71
15	Paper	-0.860 (-30.58)	1.035 (14.04)	0.634 (140.16)	0.000109 (2.34)	-4.338 (-55.79)	-0.025 (-2.34)	-0.018520 (-5.58)	-0.831 (-55.63)	22.280 (5.54)	15,382	0.78
16	Refined petroleum products	-2.538 (-29.43)	1.333 (13.17)	0.319 (33.89)	0.000476 (4.17)	-19.653 (-57.51)	-0.024 (-4.21)	-0.004872 (-0.58)	-1.904 (-46.66)	2.559 (0.58)	3,605	0.79
17	Chemicals	-1.210 (-34.47)	5.958 (13.40)	0.699 (139.97)	-0.000486 (-9.52)	-1.532 (-32.21)	0.317 (8.98)	-0.011170 (-3.19)	-0.203 (-29.11)	54.984 (3.18)	15,213	0.70
18	Pharmaceutical	-0.646 (-27.67)	4.430 (10.94)	0.708 (157.98)	-0.000278 (-6.85)	-0.497 (-31.26)	0.559 (6.62)	-0.005793 (-2.04)	-0.146 (-26.01)	39.731 (2.04)	16,728	0.69
19	Rubber & plastic	-1.480 (-43.46)	2.780 (18.74)	0.585 (105.15)	-0.000163 (-3.48)	-4.447 (-42.71)	0.037 (3.46)	-0.010069 (-3.00)	-0.532 (-46.87)	18.918 (2.99)	13,585	0.65
20	Non-metallic mineral products	-1.489 (-39.26)	20.260 (13.15)	0.636 (109.09)	-0.000641 (-9.73)	-3.125 (-32.52)	0.205 (8.99)	-0.013978 (-3.05)	-0.073 (-19.75)	190.199 (3.03)	12,976	0.65
21	Basic metals & metal products	-1.346 (-43.57)	2.525 (18.06)	0.592 (126.02)	-0.000276 (-5.74)	-3.685 (-54.11)	0.075 (5.67)	-0.015280 (-4.61)	-0.533 (-49.57)	28.676 (4.58)	17,801	0.69
22	Electronic & electrical equipment	-0.537 (-23.84)	2.325 (9.94)	0.616 (139.43)	-0.000540 (-13.01)	-0.702 (-44.52)	0.769 (12.18)	-0.017478 (-6.11)	-0.231 (-32.98)	75.721 (5.99)	22,453	0.58
23	Machinery & vehicles	-0.558 (-26.55)	1.997 (10.80)	0.636 (149.88)	-0.000462 (-12.29)	-0.428 (-31.91)	1.079 (11.33)	-0.011909 (-4.57)	-0.279 (-34.52)	42.615 (4.52)	25,723	0.55
24	Furniture	-0.848 (-23.86)	1.246 (10.40)	0.625 (95.03)	0.000125 (2.11)	-2.448 (-37.69)	-0.051 (-2.12)	-0.007341 (-1.72)	-0.681 (-36.36)	10.778 (1.71)	9,567	0.67

Notes: Estimated is Equation 4.36 (top line) using non-linear least squares. Each row represents a separate regression using panel data of extra-EU trade by mode of transport over a 2002-13 time period and calculated transport cost and transit time variables. Extremely small flows of seaborne trade by quantity are excluded. The regressions also include an importer/exporter binary variable (results omitted) to account for measurement errors in freight rates. Z-statistics are reported in parentheses.

changes in logistic patterns (j importing from k instead of i) or non-recurring air or sea shipments on particular trade routes over time.

The sign of the estimated time and cost coefficients (columns 6, 7, 9 and 10) are consistent with theory. The higher the transport or time costs, the higher the costs of a firm. Higher production costs reduce the profits of a firm, which thus reduces a firm's systematic cost component V_{ij} , indicated by the negative sign of the coefficients.

The absolute values of the time coefficients are in general smaller than the absolute values of the cost coefficients as a result of the chosen units of these variables. If time were measured in days—which is an unusual unit for air transport however—the absolute values of the cost coefficients would be higher.

Dividing the time coefficient by the cost coefficient yields the VOT (note the unit transformation from $[\text{€}/\text{kg}]$ and $[\text{h}]$ to $[\text{€}/\text{t}/\text{h}]$ and that μ cancels). For sea transport, the VOT ranges from 0.04 for food products to 1.08 $\text{€}/\text{t}/\text{h}$ for machinery and vehicles. For air transport, the VOT ranges from 19 for rubber and plastic to 190 $\text{€}/\text{t}/\text{h}$ for non-metallic mineral products. The central estimate for the total of manufacturing goods is 0.27 for seaborne and 49.9 $\text{€}/\text{t}/\text{h}$ for airborne trade. These values compare well to estimates commonly found in the freight logistics literature²⁹.

Because the VOT is formed from the ratio of the time to the cost coefficient, changes in either coefficient have a direct influence on the sign, value and significance of the VOT. For some industries, time seems to be less of an importance (e.g. in the textiles, wearing apparel, paper and furniture industries) as indicated by a positive sign and a relatively low z-statistic of the coefficient estimates of the time variable.

The high statistical significance of the estimated coefficients can be attributed at least in part to the underlying time series data as a result of forming subgroups of observations over time. Yet, in using Berkson's method, the subgroups need to be homogeneous in terms of \mathbf{x}_{ij} and consistency is only obtained if $N \rightarrow \text{inf}$. Ben-Akiva and Lerman (1985) therefore note that Berkson's method may only be applied in the case of highly aggregated data with a large number of repeated observations. The formation of subgroups over time (as imposed by the data structure of this study) therefore inevitably results into autocorrelation in variables.

Robustness check. To investigate the influence of heteroskedasticity resulting from the transformation of the MNL model into a nonlinear probability model (see Equation 4.33), I follow Guerrero and Johnson, 1982 and Kay and Little (1987) and apply the Box-Cox transformation (Box and Cox, 1964) to the odds ratio to reduce anomalies such as non-

²⁹De Jong (2008) conducts a literature review on the value of time in goods transported by different transport modes. Using the average of the reported values in De Jong (2008) and correcting them for inflation (2013 €) yields 0.019 for sea transport, 0.13 for inland waterways, 0.64 for rail, 2.67 for road, and 154 $\text{€}/\text{t}/\text{h}$ for air transport.

normality and heteroskedasticity and to generalise the logistic model. That is,

$$\left(\frac{q_{ijt}^m}{q_{ijt}^l}\right)^{\lambda_m} = \mu \beta' (\mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l)_t \quad (\forall m = 1, \dots, k \in \mathcal{C}_{ij}; m \neq l), \quad (4.37)$$

where β and \mathbf{x}_{ij}^m are as in 4.33 and

$$\left(\frac{q_{ijt}^m}{q_{ijt}^l}\right)^{\lambda_m} = \begin{cases} \ln \left(\frac{q_{ijt}^m}{q_{ijt}^l}\right); & \lambda_m = 0 \\ \lambda_m^{-1} \left[\left(\frac{q_{ijt}^m}{q_{ijt}^l}\right)^{\lambda_m} - 1 \right]; & \lambda_m \neq 0. \end{cases}$$

Assuming that there is some value of λ_m such that 4.37 holds, the generalised nonlinear probability model can be estimated using

$$\left(\frac{q_{ijt}^m}{q_{ijt}^l}\right)(\Lambda) = \begin{cases} \exp \left[\mu \beta' (\mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l)_t \right]; & \lambda_m = 0 \\ \left[1 + \lambda_m \mu \beta' (\mathbf{x}_{ij}^m - \mathbf{x}_{ij}^l)_t \right]^{1/\lambda_m}; & \lambda_m \neq 0, \end{cases} \quad (4.38)$$

for some parameter values $\Lambda = (\beta'; \lambda_m, \dots, \lambda_k)$. I estimate equation 4.38 using MLE for the total of manufactured goods and obtain a value of $\lambda^m = 0.070 (z = 46.96)$, a VOT for sea transport of 0.239 €/t/h ($p < 0.01$), and a VOT for air transport of 69.840 €/t/h ($p < 0.01$). The functional form parameter $\lambda_m > 0$ indicates some non-linearity of the odds ratio of air against sea transport. The time and cost coefficient and hence the VOTs remain however similar to the estimates in Table 4.2 and I therefore conclude that the presence of heteroskedasticity in the nonlinear probability model influences the results only marginally.

4.5 Trade, transport and prices

Are time costs quantitatively important in international trade? The VOT estimates in the previous section shed light on the importance of time costs on a per unit per hour basis for airborne and seaborne trade. To see if they are quantitatively important in the aggregate however relies on the relative influence of time costs on overall prices.

In the first part of this section I investigate if any useful information about prices can be extracted from the data using matched-partner CIF/FOB ratios and the differences in prices by transport mode. In both cases, the established theory is rejected by the data due to measurement errors and model simplifications. In the second part of this section, I use the estimates from the previous sections to quantitatively show the importance of time costs in international trade.

Matched-partner CIF/FOB³⁰ ratios - rejected by the data. Starting from bilateral trade values, the quantities imported times the per unit price of the traded good must be equivalent to the reported import value from i , mathematically: $X_{ij}^m \equiv p_{ij}^m(z_i)q_{ij}(\omega)$, where $\omega \in \Omega_i^m$. Recalling that the one plus the tax equivalent of bilateral transport costs on shipments from i to j is given by $\tau_{ij}^m \equiv 1 + \frac{t_{ij}^m + s_{ij}^m}{w_i/z_i}$ (Equation 4.11) and using the optimal price equation (Equation 4.17) for p_{ij}^m , I immediately obtain

$$\begin{aligned} \frac{X_{ij}^m}{q_{ij}^m} &= \frac{\sigma}{\sigma - 1} \left[\frac{w_i}{z_i} + t_{ij}^m + s_{ij}^m \right] \iff \\ \tau_{ij}^m &= 1 + \frac{t_{ij}^m + s_{ij}^m}{w_i/z_i} = \left(\frac{\sigma - 1}{\sigma} \right) \frac{X_{ij}^m/q_{ij}^m}{w_i/z_i}. \end{aligned}$$

Trade values³¹ X_{ij}^m and trade quantities q_{ij}^m are commonly reported in trade data. Information about country i 's production value³², $\sum_{j=1}^I q_{ij} w_i/z_i$, or the per unit production cost at the factory gate, w_i/z_i , is more difficult to obtain.

One way to approximate the production costs in country i is by dividing the reported FOB value by the quantity exported: $w_i/z_i = X_{ij}^{\text{FOB},m}/q_{ij}^m$. This transformation is possible since the FOB valuation refers to the trade value that would be invoiced in the event of sale or purchase of the exported good at the national border of the exporting country. The FOB value is therefore the trade value exclusive of any transport costs. Combining these observations with the expression from above results into the so-called "matched-partner CIF/FOB ratio"

$$\tau_{ij}^m = \left(\frac{\sigma - 1}{\sigma} \right) \frac{X_{ij}^m}{X_{ij}^{\text{FOB},m}} = \left(\frac{\sigma - 1}{\sigma} \right) \frac{p_{ij}^m}{p_i} \quad (4.39)$$

"Matched-partner" in this case refers to the two statistics that are collected for the two countries trading with each other at the national border of the exporting and the importing country.

Because $X_{ij}^{\text{FOB},m} \equiv p_i q_{ij}^m$, the expression above can also be derived from the standard no-arbitrage condition $\frac{p_{ij}^m}{p_i} \equiv \tau_{ij}^m$. As a result, the differences in prices p_i and p_{ij}^m are entirely determined by bilateral transport costs.

Although the no-arbitrage condition holds in theory, any practical implementation thereof to measure the demand elasticity with respect to transport costs remain limited. Hummels

³⁰"CIF" refers to the trade value inclusive of any trade costs (such as transport costs and tariffs), whereas "FOB" refers to trade values exclusive of any trade costs. See Appendix A.1.

³¹Note that because it is assumed that the transport costs are borne by the firm as specified by the firm's cost function in 4.9, trade flows, denoted with X_{ij} , essentially refer to a CIF valuation (cost, insurance, freight). This is the standard specification in the international trade literature. FOB values only become relevant when calculating the one plus the tariff equivalent of bilateral transport costs measure τ . τ in combination with CIF values provide the baseline to estimate the trade elasticity $1 - \sigma$.

³²Note that summing over all export flows $Y_i = \sum_{j=1}^I X_{ij}$ yields into the production value inclusive of transport costs, which is different from the production value at the factory gate $\sum_{j=1}^I q_{ij} w_i/z_i$.

and Lugovskyy (2006) show that matched-partner CIF/FOB ratios are error ridden in levels and therefore not appropriate to evaluate price elasticities of demand. This is because statistical offices in the exporting and importing country often value goods differently (e.g. due to exchange rates), track shipments more or less accurately (importers being more accurate in order to levy tariffs), and place goods under different product sub-categories (e.g. due to different product nomenclatures). In other words, is it difficult to get hold of trade values reported at the exporting and the importing country, which refer to the same bundle of goods exchanged. The matched-partner CIF/FOB ratio as a method to infer about the relative importance of transport costs on prices is rejected by the data as a result of measurement errors, rather than by the theory that is imposed on the data.

Mode specific price differences - rejected by the data. First noted by McFadden (1973), transport choice can be viewed as another source of product differentiation. Differences in trade values by transport mode should therefore contain useful information about differences in absolute levels of transport costs (see e.g. Hummels and Schaur, 2013). Consider the two subgroups $\omega \in \Omega^m$ and $\omega \in \Omega^l$, where $m \neq l$. Both these bundles are produced in county i but exported to country j using different transport modes m and l . Writing $\frac{X_{ij}^m}{q_{ij}^m} = \frac{\sigma}{\sigma - 1} \left[\frac{w_i}{z_i} + t_{ij}^m + s_{ij}^m \right]$ for each bundle separately and taking the difference between the two expressions yields

$$\frac{X_{ij}^m}{q_{ij}^m} - \frac{X_{ij}^l}{q_{ij}^l} \approx \frac{\sigma}{\sigma - 1} \left[t_{ij}^m - t_{ij}^l \right], \quad (4.40)$$

where I assumed $s_{ij}^m \ll t_{ij}^m$. By further assuming that each unit q_{ij} weighs one tonne, $X_{ij}^m/q_{ij}^m - X_{ij}^l/q_{ij}^l$ can be readily calculated from mode-specific bilateral trade data³³ to infer about the level of differences in transport costs between goods exported to j using transport modes m and l . This is because the production costs at the factory gate only depend on wage and productivity according to the laid out theory above, both of which are assumed to be invariant of the variety produced in i and therefore cancel out in Equation 4.40.

Using extra-EU trade data and Equation 4.40 I find that for manufacturing imports into the EU, goods transported via air are on average 87 Euros more expensive than goods transported via sea on a per kilogramme basis. This value is surprisingly high and far higher than the average difference of median air and ocean freight rates. In fact, using the values from Section 4.3 above, the median difference in air and sea transport costs is $2.04 - 0.27 = 1.77$ \$/kg. For the other industries defined in Appendix A, I obtain values, which range from 16 €/kg to 157 €/kg (excluding negative values). Equation 4.3 is therefore unambiguously rejected by the data.

³³ X_{ij}^m/q_{ij}^m can be calculated by dividing the CIF trade value of goods imported using transport m , by the quantity of goods imported using transport m in units of e.g. €/tonne.

The main reason for these discrepancies is the simplified representation of the marginal production cost function using only labour costs and productivity. Any other production costs such as material or capital costs are not considered, which may however be of significance. For example, the cost of materials used in the manufacturing process may be significantly higher than the cost of labour. In such cases, the value added in manufacturing these goods might be significantly lower than the actual reported trade value (the trade value measures gross manufacturing output). This is why Equation 4.40 does not hold for product groups, which differ in factor input prices other than wage w . If data of trade in value added per mode of transport would be available however³⁴, Equation 4.40 should remain sufficiently accurate to approximate differences in mode-specific transport costs, which, in theory, can be used to estimate or infer the values of the price elasticities of demand (see e.g. Eaton and Kortum, 2002 and Simonovska and Waugh, 2014). The materials price can then also be added to the systematic cost function of a firm in 4.9 to additionally account for e.g. insurance costs. The presence of cost categories other than labour would however not result into dramatic changes of the gravity equation. To see this, assume that a materials price would be added to the optimal price equation in 4.17. Just like w_i/z_i , this price would relate uniquely to each variety produced by a firm in country i and subsequently be absorbed by a fixed effect in the regression.

In sum, no valuable information can be extracted from trade data by mode of transport to learn about the influence of transport costs (and hence prices) on trade demand.

The relative importance of time costs in international trade. To quantify the relative importance of time costs, I calculate the per unit time costs using $s_{ij}^m = VOT \cdot TT_{ij}^m$ in units of [€/kg], where the VOT is taken from Table 4.2. For t_{ij}^m , I use air and sea freight values from Section 4.3 and the estimates of the AP from Table 4.2 to calculate per unit transport costs in units of [€/kg]. Because transport and time cost are calculated on a per unit basis, they are representative of the prices faced by firms to export to foreign markets.

I first evaluate relative price differences of airborne and seaborne trade using the one plus the ad valorem cost equivalent associated with the transport of goods from i to j , $\tau_{ij}^m \equiv 1 + \frac{t_{ij}^m + s_{ij}^m}{w_i/z_i}$ (Equation 4.11). I aggregate these values into an overall price measure using the Cobb-Douglas expenditure shares $\tau = \prod_{m \in M} (\tau_{ij}^m)^{\alpha_j^m}$ (Equation 4.19), where $M \equiv \{\text{sea, air}\}$ for all country pairs. I approximate α_j^m using imports and exports³⁵.

³⁴In an joint initiative, the OECD and WTO collect data on trade in value added (OECD, 2016). This trade data is however not available by mode of transport.

³⁵Domestic expenditures by mode of transport are not reported. I therefore use

$$\alpha_j^m \approx \frac{\sum_{i \in I} X_{ij}^m + X_{ji}^m}{\sum_{i \in I} X_{ij}^m + X_{ji}^m}, \quad (4.41)$$

to approximate the value of α_j^m , where X_{ij} refers j 's imports and X_{ji} to j 's exports. The former reveals j 's consumption preferences, the latter j 's production output and hence domestic consumption preferences

Because the production value at the factory gate w_i/z_i (or FOB respectively) is only reported for extra-EU exports, I restrict the sample to exports only.

Figure 4.1 displays the Kernel estimates of density of the seaborne, airborne and total iceberg transport cost measures. The distributions indicate that values of τ higher or lower than the average are less likely to occur the greater the discrepancy between those two. All curves have a positive skew, indicating that the mass of the distribution is concentrated at values lower than the average. For air transport, the curve is offset to the left because of relatively higher prices of the traded goods by air, which thus lowers the significance of overall transport costs $t_{ij}^m + s_{ij}^m$ relative to the traded value w_i/z_i (indicated by a lower elasticity of freight rates with respect to prices in Table 4.1). The deformation of the curve for air transport on the right hand side results from the inclusion of the per-unit constant AP. The Kernel density estimates I obtain for air transport are akin to the air premium values in Hummels and Schaur (2013). Because the expenditure on goods imported by air is much smaller than the expenditure on goods imported by sea transport (indicated by a small value of $1 - \alpha^s$ in Table 4.3), the aggregated iceberg transport cost measure is distributed similarly to the iceberg transport cost measure of seaborne trade. Using iceberg transport costs of goods imported by air to measure the price elasticity of demand $1 - \sigma$ would result into relatively higher values in comparison to using iceberg transport costs of goods imported by sea. This is because of the smaller variance of τ as indicated by the offset of the curve to the left. Because small differences in prices are statistically important to measure the price elasticity of demand however, I do not use the calculated price variables of this study (which in turn rely on estimated freight costs) to obtain estimates of σ .

The relatively smaller values of iceberg transport costs by air may come at a surprise, given the higher values of VOT in airborne trade in Table 4.2. To shed light on this, I move from iceberg to per unit transport and time costs. Figure 4.2 shows the relative importance of per unit time costs s in total per unit transport costs $s + t$ in percent. I approximate the aggregated measures of airborne and seaborne trade using $\prod_{m \in M} (s_{ij}^m)^{\alpha_j^m}$ and $\prod_{m \in M} (t_{ij}^m)^{\alpha_j^m}$ respectively. For the majority of bilateral trade flows by sea, per unit time costs account for approximately 35% in overall per unit transport costs. In contrast, for airborne trade, per unit time costs account for only approximately 10% in overall per unit transport costs as a result of relatively higher freight rates by air t^a . Relative to per unit transport costs therefore, per unit time costs are quantitatively more important in overall prices in seaborne trade as a result of relatively lower costs associated with the actual transport of the good by sea. Similar to Figure 4.1 above, the distribution of the aggregated values looks similar to the distribution of seaborne trade as a result of a higher expenditure share of goods imported by sea. Relatively higher values of t and s in combination with relatively lower prices w_i/z_i explain why iceberg transport costs are larger for seaborne than for airborne trade (as indicated by Figure 4.1). In the aggregated

of bundle m goods.

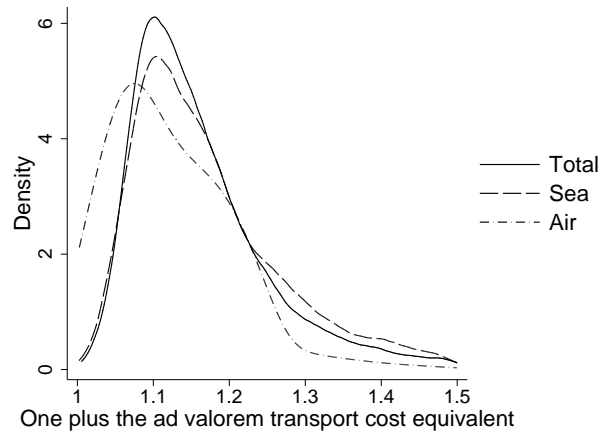


Figure 4.1: Kernel estimates of density of the seaborne, airborne and total iceberg transport cost measures of EU manufacturing exports in 2013

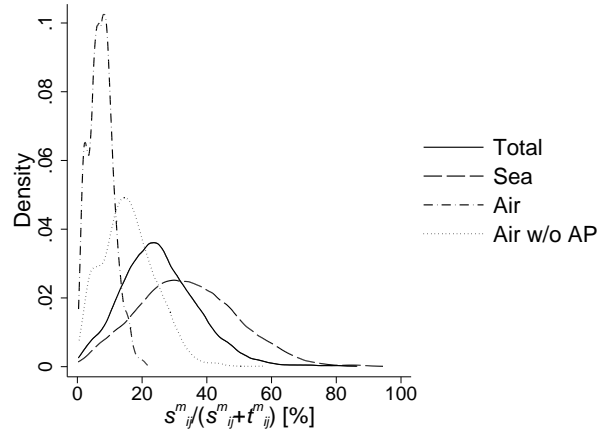


Figure 4.2: The importance of time costs in overall transport costs of EU manufacturing exports in 2013

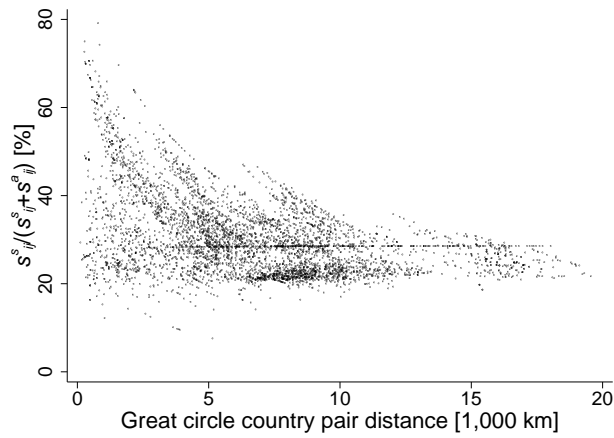


Figure 4.3: Sea time costs relative to overall time costs of EU manufacturing imports in 2013

total of manufacturing exports, per unit time costs account for approximately 25% in overall transport costs. Yet, dependent on the mix between airborne and seaborne trade and their relative differences in per unit transport and time costs between country pairs, their relative importance in overall transport costs can vary between 1% and 75%.

Figure 4.2 may be misleading in the interpretation of the differences in per unit time costs between airborne and seaborne trade. In Figure 4.3 I therefore show the relative size of per unit time costs by sea s^s in overall per unit air and sea time costs $s^s + s^a$ in percent over great circle country pair distances. For large distances, the per unit time costs associated with the transport of goods via air are significantly higher than the per unit time costs associated with the transport of goods via sea. For short distances however, the per unit time costs of seaborne trade are often larger than the per unit time cost of airborne trade due to relatively larger sea distances by country pair and hence larger transit times TT .

Considered jointly, Figures 4.1, 4.2, and 4.3 illustrate that per unit time costs are of significance in international trade³⁶. Their quantitative weight in overall prices however depends on a number of related variables and their relative quantitative importance, including per unit transport costs t , prices w_i/z_i , transit times TT , and expenditure shares α . In addition, time costs vary significantly by mode of transport and therefore influence the prices of airborne and seaborne trade unequally. The interpretation of the quantitative importance of time costs on an aggregate country-by-country level therefore remains difficult, as a result of the many possible combinations and variations of these factors. The next section investigates how changes in per unit time costs materialise into changes in overall prices and thus changes in welfare.

4.6 Counterfactuals

In this section, I analyse changes in real income associated with environmental policies in international transport. Because the drag resistance and thus fuel consumption is proportional to the squared speed in maritime transport, I investigate the policy case associated with slowing down the average sailing speed of container ships by 30% (referred to as policy case A), which would reduce their CO₂ intensity by approximately 50% (0.7^2) (Corbett, Wang and Winebrake, 2009). Furthermore, because the transport of goods via air is approximately 100 times more carbon intensive than the transport of goods via sea³⁷, I investigate the hypothetical case of shutting down the air cargo industry and transporting all goods by sea (referred to as policy case B). Policy case B is thus also illustrative for

³⁶In should be noted that the actual quantities exported are not taken into consideration in computing Figures 4.1 to 4.3.

³⁷Using typical emission indexes for jet fuel and heavy fuel oil and average energy intensities by mode of transport from Gucwa and Schäfer (2013), I obtain average CO₂ emissions intensities of 900gCO₂ per tonne-kilometre for air transport and 10gCO₂ per tonne-kilometre for sea transport.

quantifying aviation's "contribution" to the welfare gains from trade.

Both policies influence the time of goods in transit and therefore the time costs associated with importing those goods from foreign countries. Common starting point of the counterfactual exercises in this section is therefore to link changes in transport and time costs to changes in prices and subsequently to changes in real income $W_j \equiv Y_j/P_j$.

Starting with the price index P_j , I first combine Equations 4.4 and 4.6

$$P_j = \prod_{m=1}^M (P_j^m)^{\alpha_j^m} \iff (P_j)^{1-\sigma} = \prod_{m=1}^M \left(\sum_{i=1}^I (p_{ij}^m)^{1-\sigma} \right)^{\alpha_j^m}$$

Following Arkolakis, Costinot and Rodríguez-Clare (2012) and Costinot and Rodríguez-Clare (2014), it follows immediately by Shephard's Lemma that small changes in prices $d \ln P_j$ are given by

$$(1-\sigma) d \ln P_j = \sum_{m=1}^M \alpha_j^m (1-\sigma) \sum_{i=1}^I \pi_{ij}^m d \ln p_{ij}^m \iff d \ln P_j = \sum_{m=1}^M \sum_{i=1}^I \alpha_j^m \pi_{ij}^m d \ln p_{ij}^m,$$

where $\pi_{ij}^m \equiv X_{ij}^m/X_j^m$ is the share of expenditure on the bundle m goods from country i . As small changes in prices are now measured using these expenditure shares, the value of the trade elasticity $(1-\sigma)$ becomes irrelevant to quantify changes in the price index P_j .

The trade elasticity would be added again to the welfare expression if it is specified for domestic budget shares as e.g. in Arkolakis, Costinot and Rodríguez-Clare (2012) and Costinot and Rodríguez-Clare (2014). In the case however, the differences in prices are obtained from changes in transport and time costs of internationally traded goods, which are unique for each country pair and therefore not linearly related to any domestic prices changes. The standard welfare expression in international trade can therefore not be applied to the counterfactual exercises in this study.

π_{ij}^m is a variable that has already been indirectly defined in the theoretical framework. The consumption shares are given by $\alpha_j^m = X_j^m/X_j$ (Equation 4.23), mode specific budget shares are given by $\lambda_{ij}^m = X_{ij}^m/X_{ij}$ (Equation 4.8), and aggregated budget shares are given by $\lambda_{ij} = X_{ij}/X_j$ (Equation 4.24). These three expressions can be combined to substitute for $\alpha_j^m \pi_{ij}^m$ to obtain

$$d \ln P_j = \sum_{m=1}^M \sum_{i=1}^I \lambda_{ij} \lambda_{ij}^m d \ln p_{ij}^m.$$

λ_{ij}^m can be readily calculated from extra-EU imports using reported (CIF) trade values by mode of transport. To calculate λ_{ij} , total expenditures $X_j \equiv \sum_{i=1}^I X_{ij}$ (Equation 4.22) are needed. I therefore add domestic expenditures X_{jj} from UNIDO³⁸ to the extra-EU dataset before summing over all country pairs to obtain a value of X_j for each country.

Market clearing implies $X_j = w_j L_j$. Using labour in country j as the numeraire and assuming that w_j remains unaffected by policies A and B (i.e. $d \ln w_j = 0$), changes in real income can be linked to changes in prices using $d \ln W_j = -d \ln P_j$.

Assuming country j 's labour endowment to be unaffected by policies A and B requires further clarification. Because the demand for manufacturing imports is elastic, a price increase of imported goods will ultimately lead to a substitution of imported goods with goods produced domestically, thus affecting the labour endowment in country j . The labour endowment is also affected through workers in country j who are employed in the international transport sector and who are therefore subject to policies A and B. In both cases however, the relative changes in labour endowments will remain rather insignificant given that policies A and B affect prices only marginally³⁹ and that a country's contribution to the international transport sector is small in comparison to total employment in the manufacturing sector. To simplify the calculation in this section, I therefore consider changes in w_j to be small and insignificant⁴⁰ and hence $d \ln w_j \cong 0$.

Further, because domestic transport remains unaffected by policies A and B, domestic prices of goods produced and consumed in j remain unchanged. It is therefore useful to factor out p_{jj} from the expression I obtained above

$$d \ln W_j = - \sum_{m=1}^M \lambda_{jj} \lambda_{jj}^m d \ln p_{jj}^m - \sum_{m=1}^M \sum_{\substack{i \neq j \\ i=1}}^I \lambda_{ij} \lambda_{ij}^m d \ln p_{ij}^m,$$

which simplifies to

$$d \ln W_j = - \sum_{m=1}^M \sum_{\substack{i \neq j \\ i=1}}^I \lambda_{ij} \lambda_{ij}^m d \ln p_{ij}^m.$$

as a result of $\ln p_{jj}^m \equiv 0$. It should be noted however that, although p_{jj} is not of any relevance, X_{jj} still plays a significant role in the calculation of λ_{ij} (see Equation 4.24).

³⁸Trade with self (X_{jj}) for the year 2013 is approximated using 2014 UNIDO gross manufacturing output data by country minus total exports from UN Comtrade data via WITS. Missing 2014 UNIDO values are estimated using a time trend, or, in the case of missing panel data, the ratio of value added to manufacturing value added in GDP as in Mayer and Thoenig (2016).

³⁹Neither policy A nor policy B is associated with the hypothetical case of moving to autarky.

⁴⁰Quantifying the changes in w_j would require to analyse the general equilibrium impact of policies A and B

Integrating this expression before and after the policy has been introduced yields

$$\widehat{W}_j = \prod_{m=1}^M \prod_{\substack{i \neq j \\ i=1}}^I (\widehat{p}_{ij}^m)^{-\lambda_{ij} \lambda_{ij}^m} \quad (4.42)$$

where $\widehat{v} \equiv v'/v$ denotes the change in any variable v between the initial and the new partial equilibrium.

Equation 4.42 allows to calculate partial equilibrium changes in real income associated with changes in prices. The next step therefore requires to link changes in transport and time costs to changes in prices. And to accomplish this link, it can either be assumed that the shift from one mode of transport to another is insignificant or significant on the price changes \widehat{p}_{ij}^m .

Option 1: taking into account mode shifts. Common starting point is the MNL model in Equation 4.16. For a given product variety ω , a firm in i chooses a cost optimum transport mode to export to j , conditional on transport and time costs, t_{ij}^m and s_{ij}^m , and the number of available transport alternatives in the choice set \mathcal{C}_{ij} . If one of these attributes changes as a result of a new transport policy ($\mathbf{x}_{ij} \rightarrow \mathbf{x}'_{ij}$), the systematic cost function of a firm in i associated with a choice situation to export to j changes from \mathbf{V}_{ij} to \mathbf{V}'_{ij} (recall that $V_{ij}^m = \beta_0^m + \beta_3^m (t_{ij}^m + VOT^m \cdot TT_{ij}^m)$). It is therefore possible to integrate the probability associated with a particular choice situation before and after a change in \mathbf{V}_{ij} to obtain a measure of consumer surplus that is representative for the area under the demand curve measured in units of V_{ij} . Williams (1977) showed that the solution to this integral is

$$\sum_{m \in \mathcal{C}_{ij}}^M \int_{\mathbf{V}_{ij}}^{\mathbf{V}'_{ij}} \mathbb{P}_{ij}(m|\mathbf{V}) d\mathbf{V} = \frac{1}{\mu} \ln \sum_{m \in \mathcal{C}'_{ij}}^M e^{\mu(V_{ij}^m)'} - \frac{1}{\mu} \ln \sum_{m \in \mathcal{C}_{ij}}^M e^{\mu V_{ij}^m}, \quad (4.43)$$

where each summation term represents the location parameter of the maximum of independent Gumbel variates that have a common scale parameter μ , or simply, the expected maximum utility (Ben-Akiva and Lerman, 1985). The maximum of independent Gumbel variates is therefore equivalent to a firm's expected utility associated with a transport choice situation to export to j

$$\mathbb{E} \left[\max_{m \in \mathcal{C}_{ij}} (V_{ij}^m + \varepsilon_{ij}^m) \right] = \frac{1}{\mu} \ln \sum_{m \in \mathcal{C}_{ij}}^M e^{\mu V_{ij}^m}.$$

The expression in 4.43 therefore calculates the difference among expected maximum utilities of a firm before and after a change in \mathbf{x}_{ij} . Because this measure is expressed in utility terms, it is commonly divided by a coefficient of transport cost to transform it into monet-

any units⁴¹. By definition of the cost coefficient $\beta_3^m \equiv \partial V_{ij}^m / \partial t_{ij}^m$ and estimates thereof in the form of $\widehat{\mu\beta_3^m}$ from Table 4.2, it is therefore possible to transfer the expected maximum utility differences into expected marginal cost differences⁴². And because prices are modelled as a constant markup over marginal costs, the changes in prices of a firm exporting to j due to changes in \mathbf{x}_{ij} are given by

$$\widehat{p}_{ij} = \left(\frac{\sum_{m \in \mathcal{C}'_{ij}} e^{\mu(V_{ij}^m)'} }{\sum_{m \in \mathcal{C}_{ij}} e^{\mu V_{ij}^m} } \right)^{1/(\widehat{\mu\beta_3^m})} \quad (4.44)$$

Equation 4.44 imposes a priori the restriction that firms choose only one mode of transport for exporting. A change in \mathbf{x}_{ij} due to e.g. changes in any of the *air* transport attributes therefore only affects a firm, which chose to export to j using *air* transport as the preferred mode of transport in the first place. Furthermore, by Equation 4.44, all utilities are modified as a result of a shift from one mode of transport to another, due to a change in either one or many of the choice attributes in \mathbf{x}_{ij} . Equation 4.44 can therefore never be exact, as the utility difference of all alternatives is divided by a cost coefficient that is assumed to be representative for all bilateral flows (or trade routes) in the dataset. Because the policy case A predominately influences the utility associated with goods transported by sea, I transform the utility into monetary units using the coefficient estimate $\widehat{\mu\beta_3^s}$ from Table 4.2. Because the policy case B predominately influences the utility associated with goods transported by air, I transform the utility into monetary units using the coefficient estimate $\widehat{\mu\beta_3^a}$ from Table 4.2.

Given those changes in prices as a result of changes in any of the variables in \mathbf{x}_{ij} , it is now possible to link changes in any of the transport attributes to changes in real income. Substituting Equation 4.44 for the prices changes in 4.42 yields into the final expression to quantify the changes in real income (at any given year) associated with policies A and B

$$\widehat{W}_j = \prod_{m=1}^M \prod_{\substack{i \neq j \\ i=1}}^I \left(\frac{\sum_{m \in \mathcal{C}'_{ij}} e^{\mu(V_{ij}^m)'} }{\sum_{m \in \mathcal{C}_{ij}} e^{\mu V_{ij}^m} } \right)^{-\lambda_{ij} \lambda_{ij}^m / (\widehat{\mu\beta_3^m})}, \quad (4.45)$$

where

$$\left. \sum_{m \in \mathcal{C}'_{ij}} e^{\mu(V_{ij}^m)'} \right|_{\text{Policy A}} = \exp \left[\widehat{\mu\beta_0^a} + \widehat{\mu\beta_1^a} \ln \left(\frac{q_{ij}^m}{q_{ij}} \right) + \widehat{\mu\beta_3^a} \left(t_{ij}^a + \widehat{VOT}^a \cdot TT_{ij}^a \right) \right] +$$

⁴¹See for example Small (1983) and De Jong et al. (2007) for the transformation of utility into monetary units by dividing it with a cost coefficient.

⁴²Note the negative sign of the coefficient estimate $\widehat{\mu\beta_3}$ in Table 4.2. A decrease in utility therefore corresponds to an increase in marginal costs.

$$\begin{aligned}
& \exp \left[\widehat{\mu\beta}_1^s \ln \left(\frac{q_{ij}^m}{q_{ij}} \right) + \widehat{\mu\beta}_3^s \left(t_{ij}^s + \widehat{VOT}^s \cdot TT_{ij}^s / 0.7 \right) \right] \\
\sum_{m \in \mathcal{C}_{ij}}^M e^{\mu(V_{ij}^m)} \Bigg|_{\text{Policy A}} &= \exp \left[\widehat{\mu\beta}_0^a + \widehat{\mu\beta}_1^a \ln \left(\frac{q_{ij}^m}{q_{ij}} \right) + \widehat{\mu\beta}_3^a \left(t_{ij}^a + \widehat{VOT}^a \cdot TT_{ij}^a \right) \right] + \\
& \exp \left[\widehat{\mu\beta}_1^s \ln \left(\frac{q_{ij}^m}{q_{ij}} \right) + \widehat{\mu\beta}_3^s \left(t_{ij}^s + \widehat{VOT}^s \cdot TT_{ij}^s \right) \right] \\
\sum_{m \in \mathcal{C}'_{ij}}^M e^{\mu(V_{ij}^m)'} \Bigg|_{\text{Policy B}} &= \exp \left[\widehat{\mu\beta}_1^s \ln \left(\frac{q_{ij}^m}{q_{ij}} \right) + \widehat{\mu\beta}_3^s \left(t_{ij}^s + \widehat{VOT}^s \cdot TT_{ij}^s \right) \right] \\
\sum_{m \in \mathcal{C}_{ij}}^M e^{\mu(V_{ij}^m)} \Bigg|_{\text{Policy B}} &= \sum_{m \in \mathcal{C}_{ij}}^M e^{\mu(V_{ij}^m)} \Bigg|_{\text{Policy A}}.
\end{aligned}$$

A few comments are in order. First, because of linear-in-parameters utilities, the scale parameter of the Gumbel distribution, $\mu > 0$, cannot be determined. This is however less of a concern as the coefficient estimates reoccur in the counterfactual calculations as coefficient estimates multiplied by μ . Second, it is not necessary to keep track of the changes in wages w_i as the marginal production costs, $w_i q_j(\omega)/z_i$, are assumed to remain identical for all bundles of goods exported to j (see Equation 4.14). Finally, in the policy case B, the choice set \mathcal{C}_{ij} changes from air and sea transport to sea transport only (\mathcal{C}'_{ij}). The value of the systematic cost component of air transport can be determined by examining the hypothetical case of infinitely high transport costs. In this case, the systematic cost component becomes $(V_{ij}^a)' = -\infty$ as a result of $t_{ij}^a \rightarrow \infty$, and the expected maximum utility becomes $0 + \exp([V_{ij}^s]')$ as a result of $\lim_{(V_{ij}^a)' \rightarrow -\infty} \exp[(V_{ij}^a)'] = 0$.

Option 2: assuming mode shifts to be insignificant on \widehat{p}_{ij} . Alternatively, holding the mode shares fixed, the increase in prices from policy A and B can be calculated directly from the marginal cost differences. Starting from the optimal pricing equation in 4.17

$$p_{ij}^m(z_i) = \frac{\sigma}{\sigma - 1} \frac{w_i}{z_i} \tau_{ij}^m, \quad \text{where} \quad \tau_{ij}^m \equiv 1 + \frac{t_{ij}^m + s_{ij}^m}{w_i/z_i},$$

I immediately obtain

$$\widehat{p}_{ij}^m = \widehat{\tau}_{ij}^m = \frac{(\tau_{ij}^m)'}{\tau_{ij}^m}.$$

Using the expression above to substitute for prices changes in 4.42 yields into the final expression to quantify the changes in real income associated with policies A and B, holding the mode shares between country pairs fixed

$$\widehat{W}_j = \prod_{m=1}^M \prod_{\substack{i \neq j \\ i=1}}^I (\widehat{\tau}_{ij}^m)^{-\lambda_{ij} \lambda_{ij}^m} \quad \forall m \in \mathcal{C}_{ij}, \quad (4.46)$$

where

$$\begin{aligned}
(\tau_{ij}^s)' \Big|_{\text{Policy A}} &= 1 + \frac{t_{ij}^s + \widehat{VOT}^s \cdot TT_{ij}^s / 0.7}{w_i / z_i} \\
\tau_{ij}^s \Big|_{\text{Policy A}} &= 1 + \frac{t_{ij}^s + \widehat{VOT}^s \cdot TT_{ij}^s}{w_i / z_i} \\
\widehat{\tau}_{ij}^a \Big|_{\text{Policy A}} &= 1 \\
(\tau_{ij}^a)' \Big|_{\text{Policy B}} &= 1 + \frac{t_{ij}^s + \widehat{VOT}^a \cdot TT_{ij}^s}{w_i / z_i} \\
\tau_{ij}^a \Big|_{\text{Policy B}} &= 1 + \frac{t_{ij}^a + \widehat{VOT}^a \cdot TT_{ij}^a}{w_i / z_i} \\
\widehat{\tau}_{ij}^s \Big|_{\text{Policy B}} &= 1.
\end{aligned}$$

The differences in transport costs for the policy case A are calculated by scaling the travel time of goods imported via sea to account for the reduced sailing speed of container ships. For the policy case B, the transport costs associated with imports of bundle a goods (i.e. goods that would have been normally shipped by air) are calculated in the counterfactual equilibrium using ocean freight rates (i.e. a reduction) and transit time values by sea (i.e. an increase in marginal costs). The VOT however remains to be the VOT for goods imported by air.

Because FOB values, or marginal production costs respectively, are not observed in the data for extra-EU imports, I approximate them using $w_i^m / z_i^m \approx X_{ij}^m / q_{ij}^m - t_{ij}^m$.

Results. Table 4.3 contains the results of policy cases A and B, which have been calculated using options 1 and 2. Column 2 shows the approximated Cobb-Douglas share (using 4.41) of the bundle of goods imported via sea transport for information only (α_j is not used in the calculation). Column 3 reports the share of expenditure on domestic goods $\lambda_{jj} = X_{jj} / X_j$.

Columns 4 and 9 are obtained from other sources and are for reference only. Column 4 shows the results of the welfare gains from trade of a one-sector Armington model

$$G_j = 1 - \lambda_{jj}^{1/(\sigma-1)} \quad \text{where } \sigma = 6$$

as calculated in Costinot and Rodríguez-Clare (2014) for the year 2008. Column 9 shows the total CO₂ emissions from fuel combustion of the entire economy from IEA (2015).

Columns 5 to 8 contain the results of the changes in real income, $\Delta \widehat{W}_j = \widehat{W}_j' - \widehat{W}_j = \widehat{W}_j' - 1$, and columns 9 to 11 contain the results of the changes in CO₂, $\Delta \text{CO}_2 = \text{CO}_2' - \text{CO}_2$, both associated with policy cases A and B.

The relative contribution of international air transport to the overall gains from interna-

tional trade are calculated in column 12 using

$$\Delta G_j^a = \Delta \widehat{W}_{j,B2} / G_j.$$

Except for columns 4 and 12, all numbers refer to year 2013 changes.

Table 4.3: Welfare impacts associated with slow steaming and substituting nearly all air with ocean freight

(1) Country	(2) α^s [%]	(3) λ_{jj} [%]	(4) G [%]	(5) $\Delta \widehat{W}_{A1}$ [%]	(6) $\Delta \widehat{W}_{A2}$ [%]	(7) $\Delta \widehat{W}_{B1}$ [%]	(8) $\Delta \widehat{W}_{B2}$ [%]	(9) Tot.CO ₂ MtCO ₂	(10) Δ_A CO ₂ MtCO ₂	(11) Δ_B CO ₂ MtCO ₂	(12) ΔG^a [%]
Austria	48	88	5.7	-0.56	-0.12	-0.44	-1.34	65.1	-0.18	-0.25	24
Belgium	77	67	7.5	-2.06	-0.88	-0.10	-1.07	89.1	-3.34	-0.61	14
Bulgaria*	89	84	-	-0.87	-0.72	-0.25	-0.64	39.3	-0.23	-0.03	-
Cyprus	90	36	-	-1.70	-1.00	-0.20	-1.75	5.6	-0.03	-0.01	-
Czech Rep.*	92	81	6.0	-1.89	-0.21	-0.28	-0.43	101.1	-0.23	-0.07	7
Denmark	87	84	5.8	-1.03	-0.38	-0.10	-1.06	38.8	-0.52	-0.20	18
Estonia*	74	69	-	-2.15	-0.73	-0.61	-4.47	18.9	-0.04	-0.03	-
Finland	80	92	4.4	-0.51	-0.22	-0.05	-0.65	49.2	-0.28	-0.09	15
France	72	87	3.0	-0.73	-0.30	-0.11	-0.90	315.6	-3.61	-1.61	30
Germany	67	89	4.5	-0.67	-0.17	-0.20	-1.35	759.6	-3.79	-4.58	30
Greece	91	84	4.2	-0.89	-0.52	-0.03	-0.39	68.9	-0.50	-0.06	9
Hungary*	68	73	8.1	-0.49	-0.04	-1.33	-0.69	39.5	-0.11	-0.24	8
Ireland	45	67	8.0	-1.23	-0.32	-1.34	-2.89	34.4	-0.16	-0.20	36
Italy	81	91	2.9	-0.51	-0.27	-0.05	-0.57	338.2	-3.81	-1.19	20
Latvia	70	26	-	-5.05	-2.55	-1.30	-7.52	6.9	-0.06	-0.01	-
Lithuania*	87	83	-	-1.52	-0.58	-0.04	-1.07	10.7	-0.07	-0.01	-
Netherlands	80	56	6.2	-3.34	-1.28	-0.22	-2.10	156.2	-7.22	-1.29	34
Poland*	83	90	4.4	-0.83	-0.23	-0.50	-0.78	292.4	-0.72	-0.28	18
Portugal	81	91	4.4	-0.52	-0.32	-0.03	-0.55	44.9	-0.34	-0.09	13
Slovakia*	77	79	7.6	-1.96	-0.30	-0.56	-3.64	32.4	-0.13	-0.22	48
Slovenia*	91	62	6.8	-2.41	-1.09	-0.06	-0.76	14.3	-0.20	-0.02	11
Spain	87	88	3.1	-0.77	-0.38	-0.05	-0.78	235.7	-2.54	-1.03	25
Sweden	79	86	5.1	-1.09	-0.30	-0.12	-1.31	37.5	-0.60	-0.31	26
UK	68	77	3.2	-1.39	-0.44	-0.22	-2.26	448.7	-4.13	-2.94	71
Average	78	76	5.31	-1.42	-0.56	-0.34	-1.62	-	-	-	31
Sum	-	-	-	-	-	-	-	3243.0	-32.84	-15.37	-

Notes: Baseline data are 2013 extra-EU manufacturing imports. Emissions intensities for air transport are assumed to be 900 gCO₂/t.km and for sea transport 10 gCO₂/t.km. Economies in transition are indicated by a *.

Both policy cases A and B implicate price increases of goods consumed in the importing country and therefore a reduction in real income. The differences in real income in columns 4 to 7 are therefore negative. The Netherlands, Belgium and Latvia obtain relatively higher welfare impacts due to entrepôt trade. Latvia's welfare impact is even more pronounced due to its relatively small output in manufacturing (indicated by a small value of λ_{jj}).

A comparison of the policy cases A and B against each other reveals that the welfare impacts as a result of slow steaming (policy case A) are in general smaller and that slow steaming is more effective in reducing CO₂ from international trade. The smaller welfare impacts of slow steaming are a result of a relatively low VOT of goods imported by sea (see Table 4.2), whereas the higher emissions reductions are a result of larger quantities imported by sea. For the policy case B in replacing air cargo with sea cargo transport,

the higher price increases and thus welfare impacts are a result of a higher VOT of goods imported by air (offsetting the reduction in prices due to lower transport costs t_{ji}^s instead of t_{ji}^a), whereas the smaller reductions in CO₂ are a result of smaller quantities imported by air (irrespective of a 100 times higher emissions intensity).

The discrepancies in the results obtained from method 1 and 2 are a result of the many sources of non-linearity in Equation 4.44 of method 1, including the exponentiated systematic cost differences as well as their transformation into monetary units using the coefficient estimate $\widehat{\mu\beta_3}$. In addition, the price changes of relatively small or large flows of imports are not accurately predicted by method 1, as $\widehat{\mu\beta_3}$ is a parameter that is assumed to be common to all flows. Aggregating the changes by importing country however compensates for some of these differences imposed by non-linearity and common scaling parameters. For policy case A, the discrepancies in the aggregated results obtained from method 1 and 2 can be reduced to a linear scaling issue (Figure A.6). For policy case B, due to significant changes in the systematic cost function ($\exp[(V_{ij}^a)'] = 0$), non-linearities prevail and therefore also materialise into the aggregated results (Figure A.7). Given these observations, the results in columns 6 and 8 (using method 2) are my preferred results.

Putting the welfare impacts into context with the gains from trade in column 4 shows that a 30% reduction in the average speed of container ships would, on average, reduce the gains from trade by 10% (0.56/5.31), whereas a substitution of all air cargo with sea cargo transport would reduce the gains from trade by 30% (column 12). All else equal, aviation's contribution to the gains from international trade is therefore roughly 30%, which is considerable, given that only a small amount of goods (measured in tonnes) is imported by air. The relatively important contribution of airborne trade to the economy can also be seen from the consumption shares $(1 - \alpha_j^s)$ in column 2.

Putting the emissions reductions into context shows that, if the emissions from international trade were attributable to a country, then the reductions in a country's overall emissions associated with policy cases A and B would be relatively small (close to 1%). On a global basis however, the slow steaming of ships could reduce the CO₂ from international transport by a significant amount (in this case by 50%) and with only little impacts on welfare (-0.56%).

Finally, although some of the economies in transition (indicated by a *) obtain a relatively higher welfare impact, a common pattern of discrimination against these economies cannot be determined.

4.7 Summary

Time is a determinant of product differentiation in international trade. The need for, availability, and use of faster means of transport enabled the efficient trading of vertically differentiated products across borders on the one hand and shaped the landscape of the global supply chain of manufacturing firms on the other. In this chapter I model a firm's cost function to be minimising in production, transport, and time costs, and a set of distinctive transport modes that have idiosyncratic appeal. The resulting MNL model is embedded in a general equilibrium trade model and allows firms to choose a cost-effective transport mode for exporting.

Transforming the MNL model into a nonlinear probability model for empirical evaluation, I estimate the per hour per tonne VOT of goods shipped via air to be by factors of hundreds larger than the VOT of goods shipped via sea. For total manufacturing airborne trade I obtain a VOT of 50 Euros per tonne per hour, for total manufacturing seaborne trade a VOT of 0.3 Euros per tonne per hour. Controlling for marginal transport and time costs, I find that firms pay on average an additional 2,7 Euros per tonne air premium for the transport of goods by air. These costs reflect the additional costs that arise from transporting hazardous, temperature sensitive, fragile or valuable goods by air.

The transport of goods by faster means of transport in international trade is therefore costly. Yet, for products with higher unit values, these costs remain low relative to the goods price. Time sensitive goods can therefore be sold competitively in foreign markets, despite higher per unit freight rates and time costs. If vertical specialisation—as a global phenomenon of firms optimising their production processes—continues, high-tech products with relatively higher unit values will remain key components of the functioning of global supply chains. Time sensitivity will therefore play an increasingly important role in international trade, while the need for transporting time sensitive goods fast will persist or even gain momentum.

Time is also important for products with low unit values. Although per unit time costs may seem small, they represent a significant share of the overall costs associated with the transport of these goods. The reason for this is twofold. First, per unit freight costs of time insensitive goods tend to be relatively small. Second, the transit times are much longer for time insensitive goods which thus sums to relatively higher values of time costs. Relative to prices however, the costs associated with the transport of time insensitive goods remain strikingly similar to the costs associated with the transport of time sensitive goods. One of the key determinants of transport costs in international trade thus remains to be the price of the good itself.

Because the MNL model derived in this chapter is embedded in a general equilibrium model

of international trade, the model and estimated parameters can be used in counterfactual exercises to evaluate changes in real income associated with changes in time costs. I find that slow steaming could reduce the CO₂ emissions from international trade by a significant amount and with only little impacts on welfare and that aviation's relative contribution to the welfare gains from trade are on average, as large as 30%. As one of the key mitigation options in the basket of measures available, slow steaming could therefore prove to play a unique role in reducing CO₂ from the international maritime transport industry. Given the continued and rapid growth in vertically differentiated products, the international air cargo industry may play an increasingly important role in international trade, not only in terms of providing the fast and secure means of transporting goods with higher unit values across countries, but also in terms of contributing to the welfare gains from international trade within a country.

Chapter 5

Model of international tourism

This chapter develops a model of comparative advantage in international tourism. It describes a demand function with an underlying population of consumers having discrete choices over worldwide locations to undertake activities. The resulting system of equations is shown to be observationally equivalent to the standard gravity equation in international trade, implicating a parsimonious way to learn about a country's competitiveness and economic dependency on international tourism.

This chapter focuses on international tourism by air travel and therefore describes column 3 of Table 1.1. Chapter 6, which follows after this chapter, combines the trade model from Chapter 4 with the tourism model developed in this chapter to investigate changes in real income associated with environmental policies in the international aviation and maritime industry.

5.1 Background

Tourism is a key driver of economic growth and development. As an economic sector, tourism represents a major source of income for many developing countries, creates millions of jobs worldwide, and contributes significantly to export revenues. One out of every eleven jobs is related to the tourism industry, contributing to global GDP by 10% (World Bank, 2015). The WTO (2016) and UNWTO (2017) therefore promote tourism as a driver of economic growth, inclusive development, and environmental sustainability, given by the sector's importance for services exports, trade, and development, especially for small economies. Tourism is also included in the UN Sustainable Development Goal "Decent Work and Economic Growth" through creating jobs and promoting local culture and products (UN, 2015).

Tourism is a global phenomenon, already significantly large in scale, and expected to

continue to grow at an accelerated pace. In 2015, international tourist arrivals reached a total of 1.2 billion travellers, resulting into an estimated spending of US\$ 1.26 trillion in foreign countries and a 7% share of the world's exports in goods and services (UNWTO, 2016). International tourist arrivals double almost every 20 years, driven (in part) by the emergence of new tourist destinations (UNWTO, 2016) as well as the decline in air travel costs as illustrated in e.g. Schäfer et al. (2009).

While domestic tourism still represents the major source of tourism income for many advanced economies, its contribution to local employment and income is more difficult to quantify. According to the UNWTO (2016) an estimated 5 to 6 billion tourists travelled within their national borders in 2015. Although the number of global domestic tourist arrivals is 4 to 5 times higher than global international tourist arrivals, the average per person spending of domestic tourists in comparison to international tourists is approximately 4 to 5 times lower (U.S. Travel Association, 2015). A rough estimate of the world's tourism contribution to the global economy can therefore be obtained by doubling worldwide international tourism spending to obtain US\$ 2.5 trillion in total spending. To put these numbers in perspective, world exports in goods and services was US\$ 21.4 trillion and world GDP US\$ 73.4 trillion in 2015 (World Bank, 2017).

Because international tourism flows are spatial flows, a first intuition to quantifying them would be using the gravity equation. Gravity models have a long history in social sciences to explain and help predict spatial flows of commuters, air-travellers, migrants, commodities, capital, and even messages (Carey, 1858). Irrespective of their specification, these models are often found to have significant explanatory power, which led to a rapid uptake in usage (Deardorff, 1998). With respect to international tourism, studies exist in which the gravity equation is used as a tool to estimate the impact of bilateral distance, bilateral visa restrictions or immigration on bilateral tourism flows (Keum, 2008, Neumayer, 2010, 2011, Artal-Tur et al. 2013, Balli, Balli and Louis, 2016). Yet, the coefficients estimates obtained in these studies do not represent coefficient estimates of structural model parameters of theoretical macroeconomic models and are therefore not informative towards determining macro-level predictors of global tourism flows.

Motivated by these general observations, I build on Anderson, De Palma and Thisse (1992), as demonstrated in Head and Mayer (2014), and Eaton and Kortum (2002) and develop a theoretical framework for international tourism. The model features an aggregated utility and a location-specific systematic utility component. Consumers consume activities to maximise a CES objective. To undertake those activities, they choose from a set of locations worldwide and consider accommodation and travel services, which are sold or offered for sale at a lump-sum price, as well as characteristics of the destination country (climatic conditions, visa requirements, etc.). The idiosyncratic error term is assumed to be distributed Fréchet, which results into a multinomial logit model of worldwide choices of locations. Under these assumptions, the demand equation can be shown to be structurally

equivalent to the Ricardian trade model of Eaton and Kortum (2002) and observationally equivalent to the standard gravity equation in international trade (Head and Mayer, 2014), featuring bilateral accessibility and multilateral resistance terms. The model is then taken to air travel itinerary and economic tourism data to estimate the outbound tourism demand elasticity with respect to prices. For this elasticity, I find a value of four, which is similar to average values of price elasticities in international trade. Using this macro-level predictor in combination with micro-level data, the chapter then proceeds by quantifying the welfare gains from international tourism across countries. For countries with a high dependency on international tourism receipts such as the Maldives, I find that the gains from international tourism are as large as 54%, whereas for countries with a low dependency on international tourism receipts such as the US, the gains from international tourism can be as low as 0.2%.

Furthermore, given the gravity setup and the influence of common bilateral (dyadic) observables on bilateral flows, I explore the influence of a range of bilateral variables in explaining global patterns of tourism flows. Next to visa restrictions, common language, and colonial ties, I find that global tourism patterns are also explained by common preferences in activities. For example, I find that international tourism flows are 40% higher between countries where winter sports are popular.

In its entirety, this chapter contributes to both the international tourism and the international trade literature. It adds a theoretical foundation to international tourism flows that can be adapted in many ways to e.g. include heterogeneity in services, products and activities, or spillovers on manufacturing production. It therefore also contributes to the international trade literature as an additional application of the many trade models that have been developed over the past years¹, particularly also with respect to quantifying the welfare gains from globalisation².

This chapter is organised as follows. The next section presents the theoretical framework. Section 5.3 describes the data, and Section 5.4 provides a first look at this data. Section 5.5 deals with the structural estimation of the tourism demand elasticity, the discovery of global tourism patterns, and the estimation of an index of tourism competitiveness. The section after that uses counterfactual exercises to estimate the welfare gains from international tourism. Section 5.7 concludes.

¹With an overview given by Head and Mayer (2014), the main variants of the demand side models include: the Anderson-Armington model of national product differentiation (Anderson, 1979; Armington, 1969, and Anderson and Wincoop, 2003), the CES monopolistic competition (Dixit-Stiglitz-Krugman) model (derived by many authors), the CES demand with CET production model (Bergstrand, 1985), and the heterogeneous consumers model (Anderson, De Palma and Thisse, 1992). The main variants of the supply side models include: the heterogeneous industries (Ricardian Comparative Advantage) model (Eaton and Kortum, 2002) and the heterogeneous firms model (Chaney, 2008; Helpman, Melitz and Rubinstein, 2008, and Melitz, 2003).

²In particular: Arkolakis, Costinot and Rodríguez-Clare (2012) and Costinot and Rodríguez-Clare (2014).

5.2 Theoretical framework

In this section, I build on Anderson, De Palma and Thisse (1992) (as demonstrated in Head and Mayer, 2014) and Eaton and Kortum (2002) and develop a theoretical framework of international tourism. Although the model is described by explicitly referring to travel associated with leisure activities in the text below, it remains generally valid for leisure as well as business related travel activities.

Setup. There are $i = 1, \dots, I$ countries. Each individual country exhibits specific climatic, geographic, historical, and cultural characteristics A_i , which makes it a tourist destination. Consumers in country j spend the fraction α_j of their income w_j on the set of leisure activities $\{s\}$ and choose the best location $l \in i$ for it. In doing so, they become outbound or domestic tourists. They become outbound tourists if the chosen location $l \in i$ to carry out activity s is outside their home country $i \neq j$. They become domestic tourists if the chosen location $l \in i$ to carry out activity s is within their home country $i = j$.

Consumers maximize their utility by carrying out as many activities as possible. Activities are location specific. As each country is endowed with a large variety of unique locations, there is a large variety of activities to be carried out. However, I consider each location to be unique in offering the possibility to carry out only a subset of specific leisure activities $s(\omega_l)$, where $\omega_l \in \Omega$ refers to a unique variety of activities $\{s\}$. Furthermore, I consider consumers to have idiosyncratic preferences over locations $l \in i$.

As a result, individual activities s are carried out in different locations l and thus countries $l \in i$ due to location specific preferences and country-individual characteristics A_i . Because of idiosyncratic preferences however, it is possible for a representative consumer to never visit location l . In equal measures, it is also possible for a representative consumer in country j to consider location l and a representative consumer from the same or another country to consider a different location $k \neq l$ to be the prime location to carry out the same activity s . Furthermore, if consumers with identical location preferences for activity s are confronted with identical prices to carry out activity s in two different locations, then the selection over which location to travel to results from different consumer tastes. The combination of considering utility-maximising consumers to have idiosyncratic preferences over locations and each location to be unique therefore provides flexibility in the reasoning for consumers to travel. Yet these characteristics also allow to obtain a parsimonious model to explain global tourism flows.

Preferences. Consumers have utility functions u_{ji} defined over activities $s_{ji}(\omega \in \Omega_i)$, which are carried out in location $l \in i$

$$u_{ji}(\omega) = \ln [s_{ji}(\omega)\psi_{ji}] , \quad (5.1)$$

where s_{ji} is the amount spent in quantities of activities consumed and ψ_{ji} is an idiosyncratic preference shock for a particular location $l \in i$ associated with activities $s_{ji}(\omega)$.

By referring to a particular location implies referring to a set of activities $\{s\}$ because of $l \in i$ being a prime location for $s(\omega)$, where $\omega \in \Omega_i$. u_{ji} is therefore the (lower-level) utility associated with an individual activity $s_{ji}(\omega)$ in a specific location $l \in i$.

Preferences for individual locations are assumed to be distributed Fréchet with a cumulative distribution function (CDF) given by

$$F_{ji}(\psi_{ji}) = \exp \left\{ -S_i \left(\frac{\psi_{ji}}{A_i a_{ji}} \right)^{-\theta} \right\} \quad (5.2)$$

where $\theta > 0$ is the shape parameter of the CDF and therefore an inverse measure of consumer heterogeneity, which is assumed to be common to all countries. A larger θ implies less variability and thus consumers becoming less heterogeneous in their tastes over locations worldwide.

$S_i \equiv \int_{\omega \in \Omega_i} d\omega$ is a measure of the number of activities available in country i . The higher this number, the more developed the tourism sector in country i in offering activities to foreign and domestic tourists. A larger S_i implies that a high popularity draw for location $l \in i$ is more likely, as country i offers plenty of activities to choose from. The more activities, the more likely that consumers find their preferred activity within the set of available activities in country i , $\{s_i\}$. This in turn increases the probability of consumers in country j to travel to country i to undertake their preferred activity. S_i is therefore a measure of country's i popularity as a tourism destination, which is in part determined by its current state of development of the tourism sector³.

A_i and $a_{ji} \equiv \frac{A_{ji}}{A_j}$ are utility shifters. An increase in A_i or A_{ji} shifts utility upwards.

A_i is location specific and related to the set of a country's specific characteristics such as climate, geography, history, and culture as well as political turmoil, epidemics and the like. The parameters, S_i , A_i and θ can therefore be used to describe country-by-country differences in the basic Ricardian senses of absolute and comparative advantage⁴ across a continuum of locations: while S_i and A_i jointly refer to a country's absolute advantage, the parameter θ governs a country's comparative advantage across this continuum.

A_{ji} is a bilateral tourism preference parameter and measures quality aspects associated with proximity, common language and visa requirements to name a few. In combination with location specific preferences A_i however, these quality aspects are perceived relative

³The popularity parameter in the context of international tourism resembles the technology parameter in the context of international trade as in Eaton and Kortum (2002)

⁴Many theoretical frameworks in international trade build on Ricardian comparative advantage after the influential work of Dornbusch, Fischer and Samuelson (1977) and Eaton and Kortum (2002).

to the quality aspects at home, and therefore measured in terms of $a_{ji} \equiv \frac{A_{ji}}{A_j}$. An increase or decrease in A_j therefore also shifts a_{ji} downwards or upwards, holding everything else constant. For example, if average temperatures during summer in the home country j are too cold to enjoy a swim, or, for another example, if country j isn't rich in history and culture, the domestic preference parameter A_i obtains a relatively smaller value, while the bilateral preference parameter a_{ji} obtains a relatively higher value. Consumers in these countries may therefore consider travelling over longer distances or paying the additional cost of tourism visas to undertake such activities in a foreign country than they would be otherwise.

Prices. As there is a large number of available activities in each country, the market structure can be characterised by perfect competition. With no markup, prices result from the pre-set combination of accommodation and travel services, which are sold or offered for sale at a lump-sum price. The price paid by consumers therefore simply consists of the price paid for the activity $p_i(\omega)$ (inclusive of lodging, food, services, etc.) plus the expenses associated with travelling to location $l \in i$, f_{ji}

$$p_{ji}(\omega) = p_i(\omega) + f_{ji}.$$

Assuming labour as the only factor input with wage $\mathbf{w} = \{w_i\}$ and transferring the travel cost into an ad valorem travel cost measure to enter the price equation multiplicatively gives

$$p_{ji} = w_i \underbrace{\left(1 + \frac{f_{ji}}{w_i}\right)}_{\tau_{ji}}, \quad (5.3)$$

where $\tau_{ji} \geq 1$ represents the one plus the ad valorem price equivalent of bilateral travel costs. Domestic travel costs are quantitatively important for large countries and therefore also affect the reallocation of tourists such that $f_{ii} \geq 0$ and thus $\tau_{ii} \geq 1$. The specification of τ_{ji} in this model is therefore equivalent to Samuelson's (1954) "iceberg" transport cost specification, where, in this case, a transport equivalent fraction of the total amount of activities in i —that are visible to and consumed by consumers in country j —"melt" along the way.

Demand for individual activities. Let there be N statistically identical and independent consumers of activities (tourists), each with income $w_j = Y_j/N$, where Y_j is aggregate final expenditure from the tourism and non-tourism sectors. To carry out activities $s_{ji}(\omega)$, each representative consumer chooses the location giving the highest utility and then spends a fraction α_j of her income w_j .

Starting from the conditional direct utility function $u_{ji}(\omega) = \ln s_{ji}(\omega) + \ln \psi_{ji}$ (Equation 5.1), consumers maximise their utility (conditional on the chosen location $l \in i$) with

respect to the number activities consumed and subject to a budget constraint

$$\max_{\{s_{ji}(\omega)\}_{\omega \in \Omega_i}} \left(\ln s_{ji}(\omega) + \ln \psi_{ji} \right) \quad \text{s.t.} \quad p_{ji}s_{ji}(\omega) \leq \alpha_j w_j.$$

Individual demand to carry out activity s in location $l \in i$ is therefore⁵

$$s_{ji}(\omega) = \alpha_j w_j / p_{ji} \quad (5.4)$$

and zero for all other destinations.

The conditional indirect utility function of a consumer in j travelling to i to consume activity $s_{ji}(\omega)$ can therefore be written as

$$v_{ji}(\omega) = \ln(\alpha_j w_j) - \ln p_{ji} + \ln \psi_{ji}. \quad (5.5)$$

However, because consumers choose the location $l \in i$ providing the highest utility to carry out their preferred activity s , the conditional indirect utility they actually receive will be the highest across all locations $l \in i$ from all countries $i \in I$

$$v_j(\omega) = \max \{ v_{ji}(\omega); i \dots, I \}. \quad (5.6)$$

Tourism flows (Aggregate demand). Faced with these prices and utility, consumers in each country purchase individual activities in amounts $s(\omega)$ to maximise a CES objective:

$$U_j = \left(\int_{\omega \in \Omega_i} \left(e^{u_{ji}(\omega)} \right)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}} = \left(\int_{\omega \in \Omega_i} \left(e^{v_j(\omega)} \right)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}} \quad (5.7)$$

where $\sigma > 1$ is the elasticity of substitution between activities⁶. The homothetic CES preferences imply that all available locations are visited by at least some tourists from country j , while locations with higher perceived utility will proportionally receive the most tourists from country j .

Faced with a choice set of potential alternatives of locations $\{l; l \in i, i \dots, I\}$, their probability of travelling to location $l \in i$ to carry out these activities is

$$G_{ji}(v) = \Pr [v_{ji}(\omega) \geq v],$$

⁵The Lagrangian is: $\mathcal{L} : (\ln s_{ji}(\omega) + \ln \psi_{ji}) - \lambda (p_{ji}s_{ji}(\omega) - \alpha_j w_j)$. FOC are: $\partial \mathcal{L} / \partial s_{ji}(\omega) = 0 \Leftrightarrow 1/s_{ji}(\omega) = \lambda p_{ji}$, and $\partial \mathcal{L} / \partial \lambda = 0 \Leftrightarrow \alpha_j w_j = p_{ji}s_{ji}(\omega)$.

⁶The CES utility functions resemble aggregations of exponentiated utilities in multinomial choice models (Ben-Akiva and Lerman, 1985), with $\sigma/(\sigma - 1)$ being the scale parameter of the Gumbel distribution. Similar to the welfare calculations in multinomial choice models (Williams, 1977), the CES functions as described in the text can therefore be interpreted as a measure of consumer surplus. They also ensure that country j 's overall price index of consuming activities worldwide is equivalent to the Dixit-Stiglitz price index $P_j \equiv \left(\int_0^\infty p_j(\omega)^{1-\sigma} d\omega \right)^{\frac{1}{1-\sigma}}$.

which can be shown to be dependent on prices and idiosyncratic preference shocks

$$\begin{aligned}
G_{ji}(\nu) &= \Pr [\ln(\alpha w_j) - \ln p_{ji} + \ln \psi_{ji} \geq \ln(\alpha w_j) - \ln p + \ln \psi] \\
&= \Pr [-\ln p_{ji} + \ln \psi_{ji} \geq -\ln p + \ln \psi] \\
&= \Pr [-\ln p_{ji} + \ln \psi_{ji} \geq \nu] \\
&= 1 - \Pr [\ln \psi_{ji} \leq \nu + \ln p_{ji}],
\end{aligned}$$

Assuming the number of activities available in each country, $S_i \equiv \int_{\omega \in \Omega_i} d\omega$, to be i.i.d. across varieties of activities, the probability of travelling to country i , $\Pr [\nu_{ji}(\omega) \geq \nu]$, will be the same for all activities $s(\omega)$.

Fréchet for ψ implies Gumbel for $\ln \psi$, and using the price specification $p_{ji} = w_i \tau_{ji}$ from Equation 5.3, the above expression can be rewritten as the worldwide distribution of utilities $G_{ji}(\nu)$ consumers in country j face in choosing a location $l \in i$ to carry out their preferred activity $s(\omega)$

$$\begin{aligned}
G_{ji}(\nu) &= 1 - F_{ji}(\nu p_{ji}) \\
&= 1 - \exp \left\{ -S_i \left(\frac{\nu w_i \tau_{ji}}{A_i a_{ji}} \right)^{-\theta} \right\}.
\end{aligned}$$

Because consumers in country j however only choose the location giving the highest utility, the distribution $G_j(\nu) = \Pr [\nu_j \geq \nu]$ country j actually receives is⁷

$$\begin{aligned}
G_j(\nu) &= 1 - \prod_{i=1}^I (1 - G_{ji}(\nu)) \\
&= 1 - e^{-\Phi_j / \nu^\theta}
\end{aligned}$$

where

$$\Phi_j = \sum_{i=1}^I S_i (w_i \tau_{ji})^{-\theta} (A_i a_{ji})^\theta \quad (5.8)$$

is the price parameter.

In international tourism, $G_j(\nu) = 1 - e^{-\Phi_j / \nu^\theta}$ is the distribution of systematic utility across activities, whereas in international trade, $G_j(\nu) = 1 - e^{-\Phi_j p^\theta}$ is the distribution of prices across goods (Eaton and Kortum, 2002). An increase in prices p refers to a decrease in utility ν and both distributions are therefore isomorphic. The only difference between the two is specifying individual demand either to be dependent on utility (including prices) or limiting this utility to prices only (excluding idiosyncratic preferences shocks).

⁷This can be shown using

$$G_j(\nu) = 1 - \prod_{i \in I} \exp \left\{ -S_i \left(\frac{\nu w_i \tau_{ji}}{A_i a_{ji}} \right)^{-\theta} \right\} = 1 - \exp \left\{ -\nu^{-\theta} \sum_{i=1}^I S_i \left(\frac{w_i \tau_{ji}}{A_i a_{ji}} \right)^{-\theta} \right\}.$$

The model isomorphism also applies to the price parameter in 5.8. In international tourism, the price parameter additionally includes the utilities associated with location and geography as a result of the utility shifters A_i and A_{ji} . Whereas in international trade, the price parameter takes the form $\Phi_j = \sum_{i=1}^I T_i (w_i \tau_{ji})^{-\theta}$, where T_i refers to a country's state of technology. The model presented in this chapter therefore exhibits strong parallels to the Ricardian trade model described in Eaton and Kortum (2002), and it is therefore possible to simply adopt the three key properties of this model, as outlined in Eaton and Kortum (2002), for the tourism model in this chapter.

(a) The probability of consumers in country j to travel to location $l \in i$ to undertake activities is country i 's contribution to country j 's price parameter

$$\frac{S_{ji}}{S_j} = \frac{S_i (w_i \tau_{ji})^{-\theta} (A_i a_{ji})^\theta}{\Phi_j}. \quad (5.9)$$

With a continuum of activities, this probability is also the fraction of activities that consumers from country j consume from country i .

(b) The utility that consumers from country j receive by *actually travelling* to location $l \in i$ to undertake activities also has the distribution $G_j(v)$. Conditioning on the destination country therefore has no bearing on the consumers' perceived utility v_{ji} or input prices $w_i \tau_{ji}$. Destination countries with a higher state of development of the tourism sector, lower input costs, or lower barriers exploit their comparative advantage by offering a wider range of activities ω , exactly to the point at which the distribution of utility of consumers from j in i , is the same as j 's overall utility distribution. As a result, country j 's average expenditure per activity does not vary by destination country and the fraction of activities that country j undertakes in country i is also the fraction of its *expenditure* on activities in country i , $S_{ji}/S_j = X_{ji}/X_j$, where X_j refers to country j 's overall tourism spending, and X_{ji} to j 's tourism spending in i , inclusive of any travel costs.

(c) The exact price index for the CES objective function in Equation 5.7 is

$$P_j \equiv \underbrace{\left[\Gamma \left(\frac{\theta + 1 - \sigma}{\theta} \right) \right]^{\frac{1}{1-\sigma}}}_{\eta} \Phi_j^{-1/\theta}, \quad (5.10)$$

where Γ is the Gamma function and $\sigma < 1 + \theta$.

Gravity. Properties (a), (b), and (c) imply that the demand function for international tourism can be formulated as

$$X_{ji} = X_j \lambda_{ji} = X_j P_j^\theta S_i A_i^\theta w_i^{-\theta} a_{ji}^\theta \tau_{ji}^{-\theta}, \quad (5.11)$$

where $\lambda_{ji} = X_{ji}/X_j$ is the fraction of the amount spent in country i on the total number

of activities S_i of consumers from country j .

As in Eaton and Kortum (2002) for international trade models, the price index $P_j = \eta \Phi_j^{-1/\theta}$ is critical in determining spatial flows. In international tourism, the price index summarises how (i) the state of countries as a tourism destination around the world, (ii) their attractiveness as a destination country around the world, (iii) the costs associated with tourism activities around the world, and (iv) geographic barriers govern prices in country j (see Equation 5.8). In other words, it summarises how geographic barriers lead to different prices of activities worldwide, which in turn lead to deviations from purchasing power parity in tourism.

Equation 5.11 in combination with the definition of the price index is what I will refer to as gravity equation in international tourism, consisting of origin (j), destination (i) and bilateral variables (ji). If $\theta > 0$, Equation 5.11 implies that international tourism spending X_{ji} is

- increasing with country's j spending on tourism X_j ,
- increasing with j 's price index P_j as activities in the destination country i are becoming relatively cheaper if P_j increases (any increase in p_{ji} results into a higher value of P_j , holding $A_i a_{ji}$ fixed),
- increasing with the number of available activities in country i (S_i), location specific preferences A_i , and bilateral preferences a_{ji} , all of which make country i a more attractive tourist destination,
- decreasing with wage w_i in country i as higher wage means higher costs to be paid by tourists in country i (lodging, services, etc.), and
- decreasing with increasing travel costs τ_{ji} .

Equation 5.11 therefore includes variables, which are similar in their definition and interpretation to variables commonly used in international trade models, such as expenditures, price indexes, the number of products, wages and bilateral transport costs. To better see the analogy to gravity models in international trade, it is helpful to transform Equation 5.11 into its logarithmic form to obtain

$$\ln X_{ji} = \delta_j + \delta_i + \theta \ln a_{ji} - \theta \ln \tau_{ji} \quad (5.12)$$

where $\delta_j \equiv \ln X_j + \theta \ln P_j$ is the origin fixed effect, absorbing country j 's endogenous spending and price index, and $\delta_i \equiv \ln S_i + \theta \ln A_i - \theta \ln w_i$ is the destination fixed effect, absorbing country i 's endogenous number of activities and prices as well as country i 's exogenous attractiveness as a destination country. Similar to international trade models, this transformation is possible as all the variables entering Equation 5.11 can be grouped into i , j , or ji terms, thereby remaining multiplicatively separable, as I will show further below.

The logarithmic transformation shows that the gravity equation in international tourism is observationally equivalent to the gravity equation in international trade. Both models feature multilateral resistance terms (as popularized by Anderson and Wincoop, 2003, for international trade models) as well as bilateral variables, with τ referring to the same iceberg definition. The only difference between the two specifications is the demand elasticity. For the international tourism model, the key structural parameter measuring demand responses with respect to prices is $-\theta$, whereas, for an international trade model with a CES demand system, this parameter is defined as $1 - \sigma$, where $\sigma > 1$ is the elasticity of substitution between goods. As Head and Mayer (2014) notes however, there is a very strong parallel between those two. An increase in σ means that products (or activities respectively) are becoming more homogeneous. An increase in θ means that consumers are becoming less heterogeneous. Hence, both models should yield similar aggregate predictions as consumers becoming more alike in their tastes is intuitively equivalent to products (or activities) becoming more substitutable. This point is also made by Anderson, De Palma and Thisse (1992) in Proposition 3.8. (p.88), stating that the demand functions derived from a CES representative consumer model are equivalent to those generated from a multinomial logit model with the structural parameters of both models being inversely related.

Having obtained the analogy to international trade models, it is straightforward to define the remaining components of the international tourism model.

Market clearing. To close the model, I assume that markets in service provision associated with the set of activities $\{s\}$ clear. That is, country i 's income from tourism $Y_i = w_i L_i$ (inclusive of travel costs) is equivalent to the sum of i 's tourism receipts from all origins j , including i 's tourism receipts from its own home market X_{ii}

$$Y_i = w_i L_i \equiv \sum_{j=1}^I X_{ji} = \sum_{j=1}^I \lambda_{ji} X_j. \quad (5.13)$$

L_i is the number of workers in the tourism sector. Equation 5.13 ensures market clearing at the sector level.

Unlike in trade, domestic spending must equal domestic income in tourism in each country⁸

$$X_{jj} \equiv Y_{jj}. \quad (5.14)$$

Equation 5.14 ensures market clearing at the domestic level. In combination with Equation 5.13, it allows to separate domestic tourism income from international inbound tourism

⁸In trade, domestic spending is not equivalent to domestic income due to exports.

income

$$Y_i = Y_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^I X_{ji}. \quad (5.15)$$

In addition, I assume that country j 's tourism spending is equivalent to the sum of j 's spending on activities in all destination countries i , including j 's spending on activities in its own home market X_{jj}

$$X_j \equiv \sum_{i=1}^I X_{ji} = \alpha_j Y_j^E. \quad (5.16)$$

$\alpha_j = X_j/Y_j^E$ is country j 's consumption share on tourism. X_j^E denotes the total expenditure of the entire economy (denoted with an E), consisting of consumption in the tourism sector and in sectors other than the tourism sector. In equal terms, total income Y_j^E consists of income generated in the tourism sector $Y_j = w_i L_i$ plus income generated outside the tourism sector $Y_j^0 = w_j^0 L_j$

$$Y_j^E = L_j (w_j)^{\gamma_j} (w_j^0)^{\gamma_j^0}, \quad (5.17)$$

where country j 's endogenous output elasticities are given by $\gamma_j = Y_j/Y_j^E$, $\gamma_j^0 = Y_j^0/Y_j^E$, and $\gamma_j + \gamma_j^0 = 1$.

Finally, total expenditure must equal total income in each country

$$X_j^E = Y_j^E + D_j^E = w_j L_j (1 + d_n). \quad (5.18)$$

Equation 5.18 ensures market clearing at the aggregate level of the entire economy. $D_j^E = L_j d_j^E$ accounts for any exogenously determined deficits (in trade and tourism) on a per capita basis (Head and Mayer, 2014).

Jointly, Equations 5.13 and 5.16 allow to determine a country's bilateral budget shares associated with tourism activities (at home and abroad) as well as tourism wages.

Budget shares are given by $\lambda_{ji} \equiv \frac{X_{ji}}{X_j} = \frac{X_{ji}}{\sum_{i=1}^I X_{ji}}$ and remain independent of country j 's income from tourism, as can be shown by substituting X_{ji} for the gravity equation in 5.11

$$\lambda_{ji} = \frac{X_j P_j^\theta S_i A_i^\theta w_i^{-\theta} a_{ji}^\theta \tau_{ji}^{-\theta}}{\sum_{i=1}^I X_j P_j^\theta S_i A_i^\theta w_i^{-\theta} a_{ji}^\theta \tau_{ji}^{-\theta}} = \frac{S_i A_i^\theta w_i^{-\theta} a_{ji}^\theta \tau_{ji}^{-\theta}}{\sum_{i=1}^I S_i A_i^\theta w_i^{-\theta} a_{ji}^\theta \tau_{ji}^{-\theta}}. \quad (5.19)$$

Budget shares therefore remain multiplicatively separable, ensure compliance with structural gravity (Head and Mayer, 2014), and sum to one

$$\sum_{i=1}^I \lambda_{ji} = \sum_{i=1}^I \frac{X_{ji}}{\sum_{i=1}^I X_{ji}} = 1. \quad (5.20)$$

For the theoretical framework to be compliant with gravity, I adopt the specification by Arkolakis, Costinot and Rodríguez-Clare (2012) and assume a country's tourism demand system to be CES. Formally:

RESTRICTION 1: *The tourism demand system is such that for any country j and any pair of countries $i \neq j$ and $l \neq j$, $(-\theta)_j^{il} \equiv \partial \ln (X_{ji}/X_{jj}) / \partial \ln \tau_{lj} = (-\theta) < 0$ if $i = l$, and zero otherwise.*

In other words, R1 imposes the restriction to only substitute for local activities in case of any prices increases of activities consumed abroad, and rules out the possibility for country j to substitute for activities to be consumed elsewhere ($l \neq j$).

Given these observations it is now possible to also define the partial elasticity of relative outbound tourism spending with respect to travel costs, which I referred to as outbound tourism demand elasticity in the introduction

$$\epsilon \equiv -\theta = \frac{\partial \ln (X_{ji}/X_{jj})}{\partial \ln \tau_{ji}} \quad (5.21)$$

where X_{jj} refers to domestic tourism spending i.e. the total spending of all travellers choosing their home country as their destination country ($j = i$) to undertake activities $s_{jj}(\omega)$. R1 in combination with Equation 5.21 ensures that ϵ measures the proportionate change in factor proportions X_{ji} and X_{jj} associated with a change in travel costs τ_{ji} or tourism prices respectively.

This completes the description of international tourism flows in equilibrium in this economy.

5.3 Data

Data for estimating the outbound tourism demand elasticity. To estimate the outbound tourism demand elasticity ϵ using the gravity equation, data on bilateral tourism spending X_{ji} as well as data on iceberg travel costs τ_{ji} are needed.

Unlike in international trade statistics, bilateral tourism expenditures are not yet reported by statistical authorities. This problem can be overcome by transferring the dependent variable of the gravity equation from international tourism spending X_{ji} into the bilateral number of tourist arrivals N_{ji} , as will be shown mathematically in Section 5.5.1. The number of tourist arrivals by country are commonly reported by statistical authorities and collected by the UNWTO.

Like in international trade statistics however, information about iceberg travel costs or iceberg transport costs are not included in trade and tourism statistics. The data for

estimating the demand elasticity is therefore complemented with information about τ_{ji} , which can only be obtained from external sources.

The approach utilised in this chapter to jointly obtain data on X_{ji} and τ_{ji} is to first restrict international tourism flows to international tourism flows by air transport, and subsequently, to exploit air passenger itinerary data to jointly obtain values of X_{ji} and τ_{ji} . In most of the cases, air transport is the preferred and only mode of transport for long-distance travel. The dataset is therefore sufficiently accurate to estimate the demand elasticity and geographic barriers in Sections 5.4 and 5.5. To calculate the welfare gains from tourism in Section 5.6 however, tourism to nearby or neighbouring countries where surface transport (such as road and rail) in addition to air transport can be utilised becomes quantitatively important and a different dataset is therefore used instead (see further below).

For the Sections 5.4 and 5.5, bilateral tourism flows by number of tourists are extracted from the global aviation market intelligence database of Sabre (2016), containing passenger traffic and sales data over different time periods (daily to yearly) and at different aggregation levels (postal code level to country level) for airline and non-airline customers. The data is collected from bookings made via the three major global distribution systems Sabre, Amadeus and Travelport. To be compliant with the gravity equation for tourism, return trips have to be excluded. The final dataset therefore only includes flows where the point of origin country (the country passengers started their journey) is identical with the origin country (see Appendix B.2 for the details). The airfares paid by tourists to travel to foreign countries is however the airfare paid for the entire journey, including both outbound and inbound travel (i.e. including return trips). The dataset for estimation contains the air passenger itinerary passenger and airfare data in aggregated form by country and year. Table B.1 shows that numbers of international air tourist arrivals compare well to the aggregate tourism statistics of UNWTO (2016).

To be able to transfer airfares into iceberg travel costs, the dataset is complemented with international tourism receipts ($Y_i^{\text{int'l}}$) and international inbound tourists ($N_i^{\text{int'l}}$) data from the World Bank (2017). The average prices⁹ paid by international tourists in the destination country can then be approximated using

$$p_i^{\text{int'l}} = \frac{\text{international tourism receipts}_i}{\text{international inbound tourists}_i} = \frac{Y_i^{\text{int'l}}}{N_i^{\text{int'l}}} = \frac{\sum_{j=1, j \neq i}^I X_{ji}}{\sum_{j=1, j \neq i}^I N_{ji}}. \quad (5.22)$$

Because international tourism receipts from the World Bank however also include pay-

⁹The prices paid by domestic tourists may in many cases be significantly lower. One of the rare authorities reporting the number of inbound tourists as well as tourism receipts for both international and domestic tourists is the U.S. Travel Association (2015). Using Equation 5.22 for international and domestic tourism separately reveals an average domestic price of \$374 and an average international price of \$1,716 in 2015.

ments to national carriers for international transport (see Appendix B), it remains unclear whether or not $p_i^{\text{int}^1}$ includes the cost paid for travel. For the travel cost to be included in $p_i^{\text{int}^1}$, the destination country must have a national carrier *and* the consumer must have chosen this carrier to travel to the destination country. In all other circumstances, the travel cost is not included in $p_i^{\text{int}^1}$. To calculate τ_{ji} , I assume that all consumers in country j book their flights with their national carriers in country j and $p_i^{\text{int}^1}$ therefore to be exclusive of travel costs¹⁰ such that $\tau_{ji} = 1 + f_{ji}/p_i^{\text{int}^1}$. With labour as the only factor input ($p_i \equiv w_i$), this expression becomes equivalent to the definition of iceberg travel costs in Equation 5.3.

The realised dataset is used to estimate the outbound tourism demand elasticity in Section 5.5.1. A number of additional bilateral variables from different data sources as described in Appendix B are added to this dataset to investigate global tourism patterns in Section 5.5.2. To establish the results in Section 5.5.3, bilateral international tourism spending is approximated using

$$\bar{X}_{ji}^{\text{air}} \approx p_i^{\text{int}^1} \tau_{ji} N_{ji}, \quad \forall j \neq i. \quad (5.23)$$

Data for calculating the gains from international tourism. For the counterfactual exercises in Section 5.6, international tourism expenditure data, given by $X_j^{\text{int}^1} = \sum_{i \neq j}^I X_{ji}$, and total tourism receipts data, given by $Y_i^{\text{int}^1} = \sum_{j \neq i}^I X_{ji}$, both from the World Bank are combined with domestic tourism receipts data (Y_{jj}) from the World Travel and Tourism Council (WTTC, 2015). These datasets are described in detail in Appendix B.2. As domestic tourism receipts are equivalent to domestic tourism expenditures ($Y_{jj} = X_{jj}$), total tourism expenditure by country can be calculated using $X_j = X_j^{\text{int}^1} + X_{jj}$ and total tourism income using $Y_j = Y_j^{\text{int}^1} + Y_{jj}$. In equal terms, the share of domestic relative to total tourism spending¹¹ can be calculated using $\lambda_{jj} = X_{jj}/X_j$.

To calculate the output elasticity $\gamma_j = Y_j/Y_j^E$ and expenditure share $\alpha_j = X_j/X_j^E$, the dataset is complemented with gross output values (Y_j^E) for 60 countries from the OECD Input-Output tables using 2011 data (the latest available year is 2011). In combination with GDP, population, and labour data from the World Bank, gross output values are estimated for the remaining countries in the dataset (see Appendix C.2 for the details). A country's total expenditure X_j^E is obtained by subtracting net trade BOP values in goods and services from gross output. Net trade BOP data is obtained from the World Bank.

¹⁰Note that this approach in calculating this variable is different from the theoretical framework in assuming that (consistent with macroeconomic theory) the revenue generated from international travel is counted towards country i 's income. This conceptual difference, however, has no further implications on the obtained results.

¹¹It should be noted that λ_{jj} is in this case a statistic that is representative for all tourism activities in the respective country and incorporates all tourism flows by all modes of transport of international and domestic tourism. Similar to the import penetration ratio in international trade, the inbound tourism penetration ratio could then be specified as $\text{IPR} = 1 - \lambda_{jj}$.

5.4 Tourism, geography, and prices: a first look

As the gravity model is essentially derived from a MNL model, it is possible to use the IIA property and specify the odds ratio of bilateral flows relative to domestic flows¹². This normalisation is helpful to show how changes in prices relate to changes in tourism flows.

I start by deriving a ratio of foreign to domestic tourism spending. The nominator of the odds ratio is therefore given by the standard gravity equation in 5.11 in the form of $X_{ji} = X_j P_j^\theta S_i A_i^\theta w_i^{-\theta} a_{ji}^\theta \tau_{ji}^{-\theta}$. As the standard gravity equation also holds for domestic tourism ($i = j$), the denominator of the odds ratio can either be specified for country j

$$X_{jj} = X_j P_j^\theta S_j A_j^\theta w_j^{-\theta} a_{jj}^\theta \tau_{jj}^{-\theta} = X_j P_j^\theta S_j A_j^\theta w_j^{-\theta}$$

or for country i

$$X_{ii} = X_i P_i^\theta S_i A_i^\theta w_i^{-\theta}$$

respectively. To ease notation, the above expressions assume that domestic travel costs are zero $f_{jj} \equiv 0$, which thus gives $\tau_{jj} = 1$. Relative domestic preferences a_{jj} cancel by definition as the country specific preferences A must be equivalent to bilateral preferences for domestic tourism $A_j \equiv A_{jj}$, which thus gives $a_{jj} = A_{jj}/A_j = 1$.

As the choice of the reference category in the odds ratio is arbitrary, either the expression for X_{jj} or the expression for X_{ii} can serve as the denominator in the odds ratio specification.

The odds ratio can be specified as the ratio of international outbound tourism spending (spending abroad) relative to domestic tourism spending (spending at home)

$$\frac{X_{ji}}{X_{jj}} = \left(\frac{S_i}{S_j}\right) \left(\frac{A_i}{A_j}\right)^\theta \left(\frac{p_j}{p_i}\right)^\theta a_{ji}^\theta \tau_{ji}^{-\theta} = \left(\frac{S_i}{S_j}\right) \left(\frac{A_i}{A_j}\right)^\theta \left(\frac{p_j}{p_{ji}}\right)^\theta a_{ji}^\theta \quad (5.24)$$

where I used $p \equiv w$ and $p_{ji} = p_i \tau_{ji}$, and specified the inverse of the p_i/p_j price ratio with a positive price parameter θ .

The expression above shows that, relative to undertaking activities in their home country, consumers in j travel to i conditional on the relative number of available activities S , relative preferences A , and relative prices p (including the cost of travel) as well as bilateral preferences a_{ji} . As expected, country j 's relative tourism spending in i is dependent on the price ratio p_{ji}/p_j . With $\theta > 0$, the higher p_{ji} , the smaller X_{ji} , holding everything else constant. Equation 5.24 also suggests that any increase in the relative number of activities (S_i/S_j) or preferences (A_i/A_j , a_{ji}) results into larger international tourism receipts for country i .

¹²This approach is standard in the international trade literature, see e.g. Eaton and Kortum (2002) and the earlier version Eaton and Kortum (1997), as well as Head and Mayer (2000).

Are consumers willing to pay a higher price in a foreign country than at home for undertaking the same activity? According to Equation 5.24, yes.

In the case of $p_{ji} > p_j$, a consumer must have a higher utility associated with consuming the activity abroad than consuming the same activity at home (noting that if only one but the same activity is consumed in different countries it follows that $S_i = S_j$). Because A and a are utility shifters per definition, it must be that $A_i > A_j$ (location $l \in i$ preferred over location $l \in j$) and/or $a_{ji} > 1$ (e.g. visiting family or friends), both justifying a consumer to accept to pay for higher prices in the destination country. The presence of the utility shifters in the gravity equation is therefore essential to explain price differences in international tourism.

Alternatively, the odds ratio can be specified as the ratio of j 's relative spending in i , relative to i 's (relative) spending at home

$$\frac{X_{ji}/X_j}{X_{ii}/X_i} = \left(\frac{P_j}{P_i} \right)^\theta a_{ji}^\theta \tau_{ji}^{-\theta}, \quad (5.25)$$

or, in other words, as the ratio of relative international tourism receipts (foreign income) to domestic tourism receipts (domestic income). In this case, the expression indicates that, relative for consumers in i to undertake activities in their home country, consumers in j travel to i conditional on the relative price indexes P , bilateral preferences a_{ji} and travel costs τ_{ji} . As a result, if country j faces a high price index, it's relative spending in i for tourism activities will be higher. Vice versa, if P_i is high, j 's spending in i will be lower, while, at the same time, country i 's spending at home will be reducing as well. Given the large spendings in domestic tourism however, X_{ii}/X_i will decrease at a smaller rate than X_{ji}/X_j , so that overall, $(X_{ji}/X_j)/(X_{ii}/X_i)$ decreases with increasing price index P_i .

The normalised tourism share $(X_{ji}/X_j)/(X_{ii}/X_i)$ may exceed one, if—in the aggregate—the majority of consumers travelling to country i are willing to pay higher prices in the destination country as a result of a higher perceived utility a_{ji} . The aggregated data however indicates that this is rarely the case.

Figure 5.1 graphs the measure of the normalised tourism share (in logarithms) against ad valorem travel costs τ_{ji} . Consistent with theory, there is an obvious negative relationship of international tourism spending with increasing travel costs. In other words, international tourism falls with higher travel costs (or distance respectively, as indicated by Figure 5.2). The scatter in Figure 5.1 indicates heteroskedasticity at higher price levels, which is a common phenomenon when dealing with gravity equations as a result of their logarithmic transformation (Silva and Tenreyro, 2006). The influence of heteroskedasticity on the coefficient estimates will therefore receive further attention below.

The relationship between relative international outbound tourism spending and relative

prices in Figure 5.1 cannot be perfect as the influence of the price indexes and bilateral preferences is ignored. However, given the specification of the odds ratio in 5.25, the slope of the relationship in Figure 5.1 provides a rough estimate on the value of the price parameter θ . Using a simple method-of-moments estimator¹³ I obtain a value of $\theta = -12.8$.

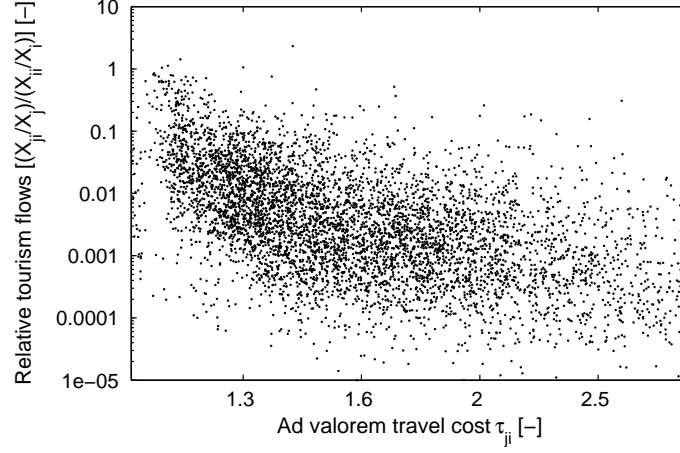


Figure 5.1: Tourism and prices. International tourism expenditures are calculated using $\bar{X}_{ji} = p_i^{\text{int'l}} \tau_{ji} N_{ji}$. Data from Sabre, the World Bank, and the WTTC. Excluded are flows where the annual number of international inbound tourists is less than 1,000. Both axes are in logarithmic scale.

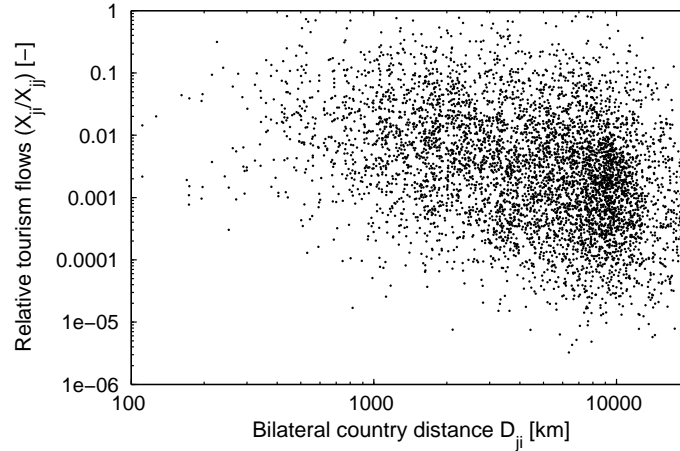


Figure 5.2: Tourism and geography. Data as in Figure 5.1. Using a simple method-of-moments estimator I obtain a value of -0.70 for the distance elasticity. Both axes are in logarithmic scale.

Lastly, a ratio of ratios can be obtained by dividing the ratio of relative international to domestic tourism receipts (Equation 5.25) by the ratio of international to domestic tourism spending (Equation 5.24), such that X_{ji} cancels

$$\frac{X_{jj}/X_j}{X_{ii}/X_i} = \left(\frac{P_i/p_i}{P_j/p_j} \right)^\theta \left(\frac{S_j}{S_i} \right) \left(\frac{A_j}{A_i} \right)^\theta. \quad (5.26)$$

¹³I divide the mean of the left-hand-side variable by the mean of the right-hand-side variable as e.g. used in Eaton and Kortum (2002).

This expression is helpful to investigate the case of a closed economy (similar to the case of autarky in international trade). In a closed economy, no international tourism will take place and all consumers in j will undertake all activities in their home country. As a result, the domestic tourism expenditure is equivalent to j 's total tourism spending $X_{jj} = X_j$. In addition, as no spending occurs abroad, the price paid by consumers in j is equivalent to j 's overall price index P_j . In a closed economy (indexed with an A), the ratio of ratios therefore simplifies to

$$\left(S_i A_i^\theta\right)^A = \left(S_j A_j^\theta\right)^A. \quad (5.27)$$

Hence, if the hypothetical case of a closed economy is imposed on the model, the model implies for a consumer in j to have no incentive whatsoever to travel to i , as the aggregate of the number of activities and location specific preferences are identical across countries.

5.5 Estimating the tourism equation

The gravity equation given by 5.11 and 5.10 in combination with 5.13, 5.16, and 5.20 comprise the system of equations that are necessary to describe international tourism in general equilibrium. Jointly, these equations determine price levels, budget shares, and wages.

Section 5.6 quantifies the gains from international tourism using counterfactual exercises. This section presents the estimation of the macro-level predictors that are necessary to calculate these counterfactuals. In particular, the first empirical exercise focuses on the estimation of the outbound tourism demand elasticity ϵ , which is one of the key parameters to calculate the gains from tourism. The second empirical exercise adds proxies for geographic barriers a_{ji} to the estimating equation to explore impediments and enhancements in international tourism flows, referred to as global tourism patterns in the text. The third and last empirical exercise estimates a country's relative tourism competitiveness by extracting useful information from estimates of the fixed effects by country.

Each exercise in this section uses a different subset of the data compiled from different tourism statistics. The initial dataset contains 46,656 bilateral flows between 216 countries in 2015. Of these observations are 30,153 (or 65%) in both directions, 2,120 (or 5%) in only one direction, and 14,383 (or 30%) account for zero flows. The empirical extent of zero flows in international tourism is therefore substantial but of smaller magnitude in comparison to international trade with approximately 50% of zero flows (Helpman, Melitz and Rubinstein, 2008). As a result of the different requirements of each of the exercises that follow, only a fraction of the observations in the initial dataset can be used. The first empirical exercise estimates the outbound tourism demand elasticity using data on airfares and international tourism receipts. As airfares are only reported in combination with tourism demand, zero flows cannot be accounted for in this regression. The second

empirical exercise estimates the impact of global tourism patterns on tourism demand using distance, common language, colonial ties, information, and variables explaining common activities. It draws upon the entire dataset by excluding airfares from the list of independent variables. Zeros are accounted for in this regression. Data limitations only arise in case of missing observations of the independent variables. The last empirical exercise estimates the tourism competitiveness across countries using domestic tourism receipts data. In this case, the data is constrained by the availability of domestic flows and the estimation technique, resulting into a dataset of tourism between 41 countries with nonzero flows.

5.5.1 Tourism, transport and prices

Using the theoretical framework outlined above and the dataset of bilateral tourism spending and prices, this section explores the range and magnitude of the price elasticity of demand in international tourism. As per the definition in Equation 5.21, the key variables of interest are bilateral tourism spending X_{ji} and iceberg travel costs τ_{ji} . The collected data reveals values of τ_{ji} in the range of 1.42 for short-distance return trips to 2.20 for long-distance return trips, and an average value of 1.88 for the entire dataset in 2015 (Table B.2). This means that, dependent on how far tourists are willing to travel, the costs associated with air travel takes up between 42% and 120% of the total cost incurred in the destination country. For tourism activities associated with long-distance travel therefore, the amount spent on transport is higher or equal than the amount spent on accommodation, goods and services in the destination country. On average, the cost paid for air travel amounts to \$1,137, corresponding to approximately 88% of the total cost incurred in the destination country. The data illustrates that consumers use a significant amount of their budget for transport relative services in tourism.

Because the definition of τ_{ji} in international tourism is structurally equivalent to the definition of τ_{ij} in international trade, it is possible to compare the average value of $\tau_{ji} = 1.88$ in international tourism (Table B.2) with the average value of $\tau_{ij} = 1.05$ in international seaborne trade (Table A.2) and conclude that the *cost share* associated with transport is on average at least a factor of ten higher in international tourism. Any cost increases associated with the transport of goods or passengers will therefore inevitably lead to relatively higher price increases in international tourism than in international trade.

As only the number of tourists travelling from j to i are commonly observed in tourism statistics, it is advantageous to perform a transformation of the dependent variable in Equation 5.11 from international tourism expenditures X_{ji} to the number of international tourist arrivals by country N_{ji} . By assuming that each *individual* tourist consumes only one activity every time a trip is undertaken, the number of international tourist arrivals is equivalent to the number of activities undertaken and hence $N_{ji} \equiv s_{ji}$. "Individual tourists" describe in this context consumers choosing a unique activity $s_{ji}(\omega)$, where $\omega \in$

Ω_i . A consumer consuming multiple activities s_{ji} is therefore counted multiple times in N_{ji} (within the observed time period), as long as each unique activity requires the consumer to travel from j to i . In all other cases, the assumption $N_{ji} \equiv s_{ji}$ is invalid and would require to specify additional variables to account for the different amounts of activities consumed.

Because $X_{ji} \equiv \int_{\omega \in \Omega_i} p_{ji} s_{ji}(\omega)$, it is possible to divide Equation 5.11 by the price p_{ji} (which is common to all activities) to obtain

$$N_{ji} = X_j P_j^\theta S_i A_i^\theta w_i^{-\theta-1} a_{ji}^\theta \tau_{ji}^{-\theta-1}, \quad (5.28)$$

where I assumed that $\int_{\omega \in \Omega_i} s_{ji}(\omega) \equiv N_{ji}$. Aside of having changed the left-hand-side variable, the price elasticities now take the value of $\epsilon - 1 = -\theta - 1$ instead of $\epsilon = -\theta$. The advantage of this model is that N_{ji} is actually observed in the data (whereas X_{ji} is not, see Section 5.3 above). Equation 5.28 therefore forms the basis of the structural estimations below, by transferring it into its logarithmic form and specifying the usual origin and destination fixed effects

$$\ln N_{ji} = \delta_j + \delta_i + \theta \ln a_{ji} + (\epsilon - 1) \ln \tau_{ji} + \varsigma_{ji}, \quad (5.29)$$

where ς_{ji} is a heteroskedastic error term as a result of the logarithmic transformation (Silva and Tenreyro, 2006) and $-\theta \equiv \epsilon$. I explore estimates of ϵ with respect to airfares (violating the iceberg form), iceberg travel costs, and bilateral distance D_{ji} (as a proxy for a_{ji}), using naive gravity (ignoring δ_j and δ_i) and structural gravity (including country fixed effects δ_i and δ_j). Table 5.1 reports the results.

Table 5.1: Tourism and prices.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	OLS					2SLS		PPML	GPML
ln airfare f_{ji} $\rho_f \epsilon$	-1.54 (0.02)	-1.82 (0.02)	—	—	—	-2.44 (0.02)	—	—	—
ln airfare τ_{ji} ϵ	—	—	-2.41 (0.08)	-5.97 (0.06)	-4.33 (0.12)	—	-6.07 (0.06)	-4.93 (0.13)	-6.13 (0.06)
ln dist. D_{ji} $\rho_d \theta$	—	—	—	—	-0.53 (0.04)	—	—	—	—
Fixed effects δ_j, δ_i	no	yes	no	yes	yes	yes	yes	yes	yes
Observations (total)	31,406	31,406	11,782	11,782	11,782	31,406	11,782	11,782	11,782
therein $N_{ji} = 0$	0	0	0	0	0	0	0	0	0
R^2	0.24	0.78	0.12	0.81	0.81	0.77	0.81	N/A	N/A

Notes: Estimated is Equation 5.29 using OLS, 2SLS, PPML, GPML, 2015 tourism data as described in Section 5.3, and the number of international tourists arrivals N_{ji} (in logs or in absolute values) as dependent variable. Observations with $\tau_{ji} > 3$ or $N_{ji} < 50$ are excluded. Each column represents a separate regression. Because f_{ji} (and thus τ_{ji}) is only reported if $N_{ji} > 0$, zeros cannot be accounted for. Robust standard errors are in parentheses.

The specifications in columns 2, 3 and 7 in Table 5.1 use airfares instead of iceberg travel costs as the independent variable to infer values of ϵ . Because of the multiplicative form of the gravity equation however, the price paid by consumers needs to be specified differently using $p_{ji} = p_i \cdot (f_{ji})^{\rho_f}$, where $\rho_f \equiv \partial \ln f_{ji} / \partial \ln \tau_{ji}$ measures the effect of airfares on

iceberg travel costs τ_{ji} . The estimated coefficients therefore take the form $(\epsilon - 1)\rho_f \equiv (-\theta - 1)\rho_f \equiv \frac{\partial \ln N_{ji}}{\partial \ln \tau_{ji}} \frac{\partial \ln \tau_{ji}}{\partial \ln f_{ji}}$. In line with existing literature¹⁴, the results in Table 5.1 indicate that demand is elastic. A 1% increase in airfares or prices respectively results into a 2% decrease in international outbound tourists (number of departures) or international tourism spending.

The specifications in columns 4-6 and 8-10 use, compliant with gravity theory, iceberg travel costs as the independent variable. In all these cases, it is possible to obtain estimates of ϵ . Equation 5.29 is estimated in columns 2 and 4 using naive gravity, and in columns 3 and 5-10 using structural gravity. The combination of structural gravity with iceberg travel costs allows to identify unbiased estimates of ϵ (Anderson and Wincoop, 2003). The coefficient estimates are in these cases compliant¹⁵ with the definition in 5.21, given by $\epsilon - 1 \equiv -\theta - 1 = \frac{\partial \ln (N_{ji}/X_{jj})}{\partial \ln \tau_{ji}}$. The outbound tourism demand elasticity takes a value of $\epsilon = -5.97$ (column 5). Controlling for endogenous price indexes, income and number of activities in each country by including country fixed effects in the regression therefore has a strong effect on the estimated coefficients. Because airfares are strongly correlated with distance (0.54), much of the variation in iceberg travel costs is explained by bilateral distance and the absolute value of ϵ therefore drops slightly in column 6.

Because prices and airfares are determined in a supply-demand equilibrium, they are endogenous. A valid instrument for airfares is the amount of airfare related taxes and surcharges paid by air travellers for their journey. These additional costs nowadays account for a substantial part of the overall airfares paid by consumers (see Table B.2). Further, as they are imposed by civil aviation authorities and local governments upon national and international airlines, they are exogenous. The standard statistical tests indicate that airfare related taxes and surcharges are a strong and valid instrument for τ and that the model is identified. Instrumenting on iceberg travel costs using iceberg taxes results into a slightly higher elasticity estimate (column 8). With a value of the outbound tourism demand elasticity of $\epsilon = -6.07$ it follows that a 1% increase in iceberg travel costs results into a 6% reduction in outbound tourism expenditures or a 6% reduction in international outbound tourists respectively.

Because $\theta \equiv -\epsilon$ is defined as the shape parameter of the underlying CDF, it is representative for the consumers heterogeneity in activities offered worldwide. A high value of θ generates less heterogeneity and indicates a higher substitutability of activities across countries. While a value of $\theta = 6.07$ certainly indicates high substitutability, it is similar to the parameter estimates in international trade, with an average value of approximately

¹⁴Similar coefficient estimates of air passenger demand elasticities w.r.t airfares—using a specification without fixed effects—can be found in e.g. Verleger (1972) and Dray et al. (2009).

¹⁵Because of the inclusion of country fixed effects in the regression, the dependent variable $\ln(N_{ji}/X_{jj})$ can be specified without accounting for domestic spending X_{jj} .

five (Head and Mayer, 2014), reflecting small heterogeneity of the goods consumed or a high substitutability of goods respectively.

As OLS on a log-linear model becomes an inconsistent estimator in the presence of heteroskedasticity (Silva and Tenreyro, 2006), I explore the robustness of the coefficient estimates in 5.33 using Poisson PML (PPML) and Gamma PML (GPML) as proposed in Head and Mayer (2014) in columns 9 and 10. As the coefficient estimates obtained from OLS, PPML and GPML are similar, the model is well specified and the error term appears to be approximately log-normal with a constant variance¹⁶. In the prevailing case of using a large sample, similar OLS and GPML and smaller PPML coefficient estimates (in absolute value) indicate¹⁷ that prices have a non-constant elasticity, a phenomenon that occurs frequently in gravity regressions. ϵ therefore varies across country pairs due to barriers to market (e.g. distance). The pattern of the variability of the price elasticity (i.e. whether or not it is declining or increasing with easiness of market) will be investigated in the next section.

Are travel costs purely ad valorem in international tourism so as to comply with the multiplicative form of the tourism gravity equation? Using a similar specification as in Hummels and Skiba (2004), the elasticity of airfares with respect to prices can be investigated by writing airfares as a function of prices, the number of outbound tourists by destination country, and the distance travelled

$$\ln f_{ji} = \beta_0 + \beta_1 \ln p + \beta_2 \ln N_{ji} + \beta_3 \ln D_{ji} + \varepsilon_{ij}, \quad (5.30)$$

where β_1 is the coefficient of primary interest. β_1 is measured using either prices inclusive of transport costs p_{ji} or exclusive of transport costs $p_i = w_i$. The error term captures any unobserved cost shifters and measurement errors. Equation 5.30 is estimated using OLS and 2SLS using the same data as described in Section 5.3.

Table 5.2: Travel costs and tourism prices.

(1) Variables (in logs)	(2) OLS		(3) 2SLS		(4) OLS		(5) 2SLS	
Price p_{ji} [\$/person]	0.478	(0.009)	0.202	(0.026)	—	—	—	—
Price p_i [\$/person]	—	—	—	—	0.164	(0.006)	0.134	(0.018)
Quantity N_{ji} [PAX]	-0.049	(0.001)	-0.054	(0.001)	-0.059	(0.001)	-0.059	(0.001)
Distance D_{ji} [km]	0.339	(0.006)	0.420	(0.009)	0.450	(0.006)	0.455	(0.006)
Observations	11,401		11,401		11,401		11,401	
R ²	0.82		0.79		0.76		0.76	

Notes: Estimated is Equation 5.30 using OLS and 2SLS using the log of airfares in [\$/PAX] as dependent variable. Prices are instrumented by destination GDP per capita. Robust standard errors are in parentheses.

The results in Table 5.2 illustrate that travel costs in international tourism are in part determined by the prices paid in the destination country. Although this effect is relat-

¹⁶Similar PPML and GPML estimates that are distinct from OLS would indicate that OLS estimates are unreliable and that heteroskedasticity is a problem (Head and Mayer, 2014).

¹⁷Major divergence between PPML and GPML coefficients would be a sign of model mis-specification (Head and Mayer, 2014).

ively small (a 1% increase in price results into a 0.2% in airfares), it is significant. More importantly however, the elasticity of airfares with respect to prices is far from a unitary elasticity value imposed by the transformation of airfares into iceberg travel costs to comply with the multiplicative form of gravity using Equation 5.3. In other words, airfares are not "purely ad valorem" to tourism prices and the iceberg assumption on travel costs is therefore rejected. In international trade, estimates of β_1 are in the range of 0.5-0.7 (see Table 4.1 and Hummels and Skiba, 2004), and although these estimates are also sufficiently different from a unitary elasticity value, the iceberg assumption could at least be somewhat justified in an empirical context. In contrast to trade, estimates of the demand elasticity ϵ using iceberg travel costs in international tourism need to be interpreted with caution. Because the elasticity of airfares with respect to prices is lower than the unitary elasticity value imposed by the iceberg assumption, estimates of the demand elasticity with respect to iceberg travel costs in international tourism as shown in Table 5.1 are biased upwards. In other words, as the ad valorem component of iceberg travel costs is small, the coefficient estimate is biased upwards due to smaller variance. As airfares are determined on a per unit rather than an ad valorem basis, they should also be specified in per unit terms using f_{ij} in the gravity equation. Such a specification would violate the multiplicative form of the gravity equation however, and the demand elasticity with respect to per unit travel costs is therefore biased downwards. In other words, because the partial elasticity of iceberg travel cost with respect to per unit travel costs $\rho_f \equiv \frac{\partial \ln \tau_{ji}}{\partial \ln f_{ji}}$ is not accounted for in the regression, the coefficient estimates is biased downwards due to larger variance. The actual value of the outbound tourism demand elasticity with respect to airfares most probably therefore lies somewhere between the two estimates in columns 7 and 8 in Table 5.1 with a value of approximately four. This value is chosen as the preferred estimate to calculate the gains from tourism in Section 5.6.

The additional coefficient estimates obtained in Table 5.2 illustrate the importance of non-price portions, such as distance and quantity, in determining per unit airfares. The elasticity of per unit airfares with respect to quantity is negative, indicating that per unit travel costs are falling in market size due to transport economies of scale.

5.5.2 Global tourism patterns

This section explores common patterns across countries in international tourism. A common pattern can be identified if countries engaging in tourism activities exhibit similar preferences with respect to common bilateral observables. Using the gravity equation, it is therefore possible to investigate the impact of e.g. proximity, common language, colonial ties, and even common activities (as implied by the theory) on international tourism flows. Common differences in prices across countries are difficult to measure and are therefore not included in this section (see the previous section for estimates of the price elasticity of

demand).

Proximity is measured using the great circle distance between countries. Distance is correlated with airfares and therefore also serves as proxy for prices in the regression. To measure the influence of proximity on the value of the estimated distance elasticity, the continuous distance variable in logs is interacted with a categorical distance variable d_k ($k = 1, \dots, 6$), where d_k is the distance between j and i lying in the k th interval.

All other variables (information, visas, language, and activities) describe the bilateral preference term a_{ji} . In particular, by assuming the underlying function to be log-linear, a_{ji} is described using

$$\ln a_{ji} = \ln i_{ji} \times p_h + ll \times d_k + v + l + c + s + o + \varsigma_{ji}, \quad \forall j \neq i \quad (5.31)$$

where i is the amount of information exchanged between j and i , ll is an indicator variable if the preferred direction of travel is mainly north to south (or south to north) as opposed to east-west¹⁸, v is the effect of tourism visa requirements between j and i , l is the effect of j and i sharing a language, c is the effect of j and i having colonial ties, s is the effect of both countries having at least one major ski resort, and o is the effect of both countries being near a coast. All these variables are described in detail in Appendix B.

Common language and colonial ties are proxies for geographic barriers that are commonly used in the trade literature (Head and Mayer, 2014). Frequently used in the international tourism literature is an indicator variable for visa requirements (see e.g. Neumayer, 2010). Having one major ski resort and being near a coast are proxies for common winter and summer activities across countries.

Like in international trade, information frictions may be quantitatively important in international tourism. Allen (2014) finds that it is costly to learn about the market conditions in foreign countries in international trade, which, intuitively, might also apply to international tourism activities. Hence, if information barriers are large, consumers in country j have difficulties to establish a benchmark for the location specific preferences A_i and the number of available activities S_i in country i .

The impact of information barriers on international tourism is measured using data of internet users (per 100 people) per country from the World Bank, by assuming that the lower value of internet users of the matched partners j and i is indicative for the amount of information exchanged between the two countries

$$i_{ji} \equiv \min [\text{internet users}_j, \text{internet users}_i]. \quad (5.32)$$

¹⁸The preferred direction of travel is measured using the absolute difference in degrees of latitude between the country centroids, relative to the absolute difference in degrees of longitude between the country centroids.

To measure the influence of relatively large and relatively small tourism flows on information barriers, the continuous variable i_{ji} is interacted with a categorical demand variable p_h in Equation 5.31, where $p_h (h = 1, \dots, 6)$ is the number of tourists travelling between j and i lying in the h th demand interval.

Imposing the above specifications of proximity, information, visa, language, and common activities, Equation 5.28 becomes

$$\ln N_{ji} = \delta_j + \delta_i - \theta \ln D_{ji} \times d_k + \theta \ln i_{ji} \times p_h + ll \times d_k + v + l + c + s + o + \varsigma_{ji}, \quad \forall j \neq i, \quad (5.33)$$

where the coefficients for the binary variables (ll , v , l , c , s , and o) have been suppressed for notational simplicity. The error term ς_{ji} captures geographic preferences (or barriers respectively) from all other factors. The six distance intervals (in kilometres) are: [0,1500); [1500,3500); [3500,6500); [6500,10000); [10000,14000); [14000,maximum]. The six demand intervals (in numbers of international tourism arrivals) are: [0,100); [100,500); [500,2000); [2000,10000); [10000,100000); [100000,maximum].

Because the log transformation of the variables may prevent the error term of having a zero conditional expectation (Silva and Tenreyro, 2006), I explore the robustness of the coefficient estimates in Equation 5.33 using PPML and GPML as above. Table 5.3 contains the results and indicates that the error term is robust against heteroskedasticity.

The results indicate that the distance elasticities decline with easiness of market. That is, the further the countries are apart, the higher the distance elasticity. As distance is correlated with airfares, a declining pattern of the outbound tourism demand elasticity ϵ with increasing distance can be inferred, implying that demand is relatively less elastic for tourism to nearby or neighbouring countries and relatively more elastic for long-distance tourism activities. Higher elasticities yield into smaller welfare impacts on the consumption side. If the tourism sector is dependent on international inbound tourists travelling long distance however (such as remote island countries), small price changes will lead into relatively larger reductions in tourism demand and thus higher impacts in terms of a country's income (see Equation 5.37 below).

Many papers provide evidence of the variability of elasticities in international trade with easiness of market (e.g. Novy, 2013; Helpman, Melitz and Rubinstein, 2008). The results in this study illustrate that the same declining pattern applies to international tourism. The related PPML and GPML estimates indicate robustness of this pattern against heteroskedasticity and against including zero flows, where $N_{ji} = 0$. Zero tourism flows occur naturally in the model as consumers select the location $l \in i$ providing the highest utility to carry out their preferred activity (see Equation 5.6). The probability of consumers in country j to travel to some other location to undertake this activity can therefore also be

Table 5.3: Global tourism patterns.

(1)		(2)	(3)	(4)	(5)	(6)	(7)
Variable		OLS		PPML		GPML	
		est.	s.e.	est.	s.e.	est.	s.e.
Distance [0,1500km)	θd_1	-0.89	(0.06)	-0.05	(0.06)	-1.38	(0.08)
Distance [1500km,3500km)	θd_2	-0.86	(0.06)	-0.11	(0.06)	-1.39	(0.07)
Distance [3500km,6500km)	θd_3	-0.90	(0.05)	-0.26	(0.05)	-1.42	(0.06)
Distance [6500km,10000km)	θd_4	-0.96	(0.05)	-0.30	(0.05)	-1.47	(0.06)
Distance [10000km,14000km)	θd_5	-0.98	(0.05)	-0.32	(0.05)	-1.47	(0.06)
Distance [14000km,maximum]	θd_6	-0.99	(0.05)	-0.38	(0.05)	-1.49	(0.06)
Information [0,100N)	$\theta_{i,j;p_1}$	1.08	(0.02)	2.54	(0.17)	0.98	(0.03)
Information [100N,500N)	$\theta_{i,j;p_2}$	0.56	(0.02)	1.39	(0.14)	0.45	(0.03)
Information [500N,2000N)	$\theta_{i,j;p_3}$	0.28	(0.02)	0.80	(0.13)	0.20	(0.03)
Information [2000N,10000N)	$\theta_{i,j;p_4}$	-0.08	(0.02)	0.34	(0.13)	-0.30	(0.04)
Information [10000N,100000N)	$\theta_{i,j;p_5}$	-0.62	(0.03)	-0.34	(0.12)	-0.83	(0.06)
Information [100000N,maximum]	$\theta_{i,j;p_6}$	-1.51	(0.08)	-1.38	(0.12)	-1.59	(0.08)
Direction N-S/E-W [0,1500m)	θlld_1	0.16	(0.06)	0.00	(0.08)	-0.13	(0.16)
Direction [1500km,3500km)	θlld_2	-0.08	(0.04)	0.02	(0.07)	-0.13	(0.06)
Direction [3500km,6500km)	θlld_3	-0.17	(0.03)	0.22	(0.10)	-0.28	(0.04)
Direction [6500km,10000km)	θlld_4	-0.01	(0.03)	0.09	(0.08)	-0.18	(0.04)
Direction [10000km,14000km)	θlld_5	-0.26	(0.04)	-0.08	(0.13)	-0.62	(0.06)
Direction [14000km,maximum]	θlld_6	-0.41	(0.06)	-0.44	(0.16)	-0.74	(0.08)
Visa restrictions	θv	-0.43	(0.02)	-0.55	(0.08)	-0.44	(0.03)
Common language	θl	0.83	(0.02)	0.51	(0.06)	1.02	(0.04)
Colonial ties	θc	0.20	(0.03)	0.33	(0.11)	0.25	(0.04)
Ski resort	θs	0.44	(0.03)	0.01	(0.09)	0.20	(0.04)
Near coast	θo	0.05	(0.03)	0.06	(0.07)	0.16	(0.04)
Fixed Effects δ_j, δ_i			yes		yes		yes
Number of observations (total)			26,172		32,232		32,232
therein $N_{ji} = 0$			0		6,060		6,060
R^2			0.90		N/A		N/A

Notes: Estimated is Equation 5.33 using 2014 data (see Appendix B). Standard errors are in parentheses. Dependent variable for OLS is $\ln N_{ji}$ and for GPML and PPML $N_{ji} \geq 0$.

zero. The data illustrates that this is the case for approximately 20% of all observations in the restricted dataset, the majority of which are flows between small countries over long distances.

Information barriers are quantitatively important for small tourism flows. That is, the more information exchanged between two countries, the higher the probability that they also engage in international tourism activities with each other. Vice versa, if information is limited, consumers in country j cannot learn about country's i attractiveness A_i and available activities S_i and consumers in country j therefore engage less in international tourism activities with country i , holding everything else constant. As indicated by the coefficient estimates, the effect of the amount of information exchanged becomes smaller and eventually negative with increasing demand. It becomes smaller as information becomes relatively less important with an increasing population or an increasing number of international tourist arrivals N respectively, as more information is exchanged between the two countries in absolute terms, given by $N_{ji} \times i_{ji}$. It eventually becomes negative, once relative tourism demand on any given tourism route becomes larger than the fraction

of internet users per 100 people $\lambda_{ji} > i_{ji}$. On busy and well established tourism routes, the lower number of internet users per 100 people between country pairs is therefore not indicative to measure the effect of information barriers on tourism demand.

The results in Table 5.3 also indicate that for tourism to nearby or neighbouring countries, tourists prefer to travel north to south (or south to north), rather than east to west (or west to east respectively). All else equal, the advantage of travelling north to south is the chance of entering a different climate zone at the destination country. In other words, it is more likely that a tourist confronted with identical prices in two locations may choose the location which is further south rather than east or west to enjoy good weather. For long distance tourism however, the preferred direction of travel is east-west (as indicated by changing sign of the coefficient estimates) as a result of the earth's topography (travel between continents). This pattern becomes more pronounced when controlling for zero tourism flows using PPML but less so using GPML. Robust and significant results of this pattern are however obtained once the distance variable is excluded. This is because of a strong correlation between the distance variable D_{ji} and the indicator variable of the preferred direction of travel ll .

The additional cost of and effort to obtain a tourist visa reduces the incentive for consumers to visit a foreign country to undertake activities. The coefficient estimates indicate that outbound tourism demand decreases by over 40% if bilateral visa restrictions are in place. Neumayer (2010) finds even higher coefficient estimates of this variable, ranging from -0.7 to -1.0.

The impact of common official language on international tourism is large and robust. The results indicate that bilateral tourism flows are almost twice as large if countries share the same official language, the same national language, or a language spoken by at least 20% of the population in either country. Artal-Tur et al. (2013) find a similar value of this coefficient estimate using global tourism data from the UNWTO. For comparison, the mean coefficient estimate of this variable in international trade is only 0.33 (Head and Mayer, 2014). Intuitively, speaking the same language should have a higher influence on international tourism than on international trade. This is because a large part of international tourism might be due to travellers visiting family and friends who live in foreign countries whereas in international trade, common language is associated with familiarity in foreign products or bilateral trade relationships. In international tourism therefore, common language might have a more immediate impact on bilateral flows than in the case of international trade.

The coefficient estimate for colonial ties is similar to values in Neumayer (2011) and Artal-Tur et al. (2013), and similar to typical coefficient estimates in international trade (Head and Mayer, 2014).

And finally, the results indicate that bilateral tourism patterns can also be explained by common activities. The coefficient estimates for common winter activities suggest that international tourism flows are higher between countries that have at least one major ski resort. Growing up in a country where it is possible to learn to ski, tourists may seek to also explore other ski resorts worldwide and therefore engage in international tourism activities. And these activities may be more common among those countries having at least one major ski resort, as in all other cases, it is more difficult to (even start) engaging with such winter activities like skiing. One might think that such pattern may also be apparent for typical summer activities like swimming, sailing or scuba diving. In this case however, those activities are not bound to a country's topology or geography. For instance, someone could learn to swim in a lake or in an indoor swimming pool. Being near a coast is therefore not a good indication of tourists travelling to foreign countries to undertake similar summer activities as indicated by the low significance and volatility in the coefficient estimates in Table 5.3. The main challenge lies therefore in finding bilateral variables explaining common preferences in activities that coincide with certain country characteristics, be it geographical, topological, cultural or climatological to name a few. The primitive results obtained in this study indicate that the search for variables explaining common preferences in activities may prove to be successful in explaining global tourism patterns.

5.5.3 Tourism competitiveness

Gravity equations relate bilateral flows to relative differences in the countries' characteristics and the geography between them. As demonstrated by Eaton and Kortum (2002) for international trade models, estimating the gravity equation with origin and destination country dummies therefore also provides a way to learn about the state of a country's competitiveness in tourism.

Starting from the odds ratio of international outbound tourism spending relative to domestic tourism spending (Equation 5.24)

$$\frac{X_{ji}}{X_{jj}} = \frac{S_i A_i^\theta w_i^{-\theta}}{S_j A_j^\theta w_j^{-\theta}} a_{ji}^\theta \tau_{ji}^{-\theta},$$

specifying the inbound tourism effect I as

$$I_i \equiv \ln S_i + \theta \ln A_i - \theta \ln w_i \quad (5.34)$$

and taking logs gives

$$\ln \frac{X_{ji}}{X_{jj}} = I_i - I_j + \theta \ln a_{ji} - \theta \ln \tau_{ji} - \theta O_j,$$

where, in addition to the specified variables, an overall outbound tourism effect has been included, denoted O_j , which will be described further below.

By definition, I_i reflects a country's comparative advantage adjusted for its labour costs. More specifically, I_i provides a way to learn about a country's tourism competitiveness as a service provider, both in terms of its number of activities offered (S) and its popularity as a destination country (A), adjusted for its labour costs (w). For example, country i may compensate for higher labour costs and therefore remain (relatively) competitive if it e.g. offers a rich set of tourism activities or is popular among tourists as a destination country. In this case, the index I_i obtains a positive value: $\ln S_i + \theta \ln A_i > \theta \ln w_i$. Vice versa, a country's tourism competitiveness is lower (relative to all other countries in the dataset) if $\ln S_i + \theta \ln A_i < \theta \ln w_i$.

The inbound tourism effect I_i is therefore a measure that is similar to the WEF's Travel and Tourism Competitiveness Index (TTCI; WEF, 2015). The TTCI is a normalised, weighted average of quantitative and qualitative indicators and has become widely accepted within government, industry, and academia. As a verification exercise, the results obtained in this section are therefore compared against the TTCI.

The outbound tourism effect O_j captures the willingness of travellers to exploring new frontiers in visiting foreign countries and should therefore not be confused with the general term of tourism openness¹⁹. The higher the value of O_j , the more countries are visited by tourists from country j . O_j is therefore a measure of a country's diversity in international tourism across countries.

I calculate the odds ratio $\ln X_{ji}/X_{jj}$ using data from Sabre, the World Bank, and the WTTC (see Section 5.3). Because I_i is estimated relative to all other countries in the dataset, I restrict the dataset for this estimation to the set of countries who are engaging with *all other* countries in tourism activities, leaving 41 countries in the dataset²⁰ and $41 \times 41 - 41$ informative observations. Because the odds ratio of international outbound tourism spending relative to domestic tourism spending is vacuous if $j = i$, the dataset does not contain any diagonal elements, reducing the number of observations by 41.

Due to the restricted dataset, categorical interaction variables and variables with a non-constant elasticity (such as information barriers and the direction of travel) are excluded from the log-linear function of bilateral preferences a_{ji} in Equation 5.31. In combination

¹⁹Tourism openness is the inbound plus outbound tourism expenditure OECD (2012). A country's tourism openness is therefore embedded in the inbound tourism effect I_i . In contrast, if O_j is specified for international trade models as in Eaton and Kortum (2002), the index j would indicate the importing country and O_j would therefore be a measure of a country's openness.

²⁰The dataset for estimation does therefore not contain any zero flows. Whether or not tourism flows exist between country pairs which are missing in the dataset remains unknown. Missing observations can either be a result of zero flows (no actual bilateral tourism activities between countries) or reporting issues (availability of data).

with the definition of the inbound and outbound tourism effects I_i and O_j , the gravity equation then becomes

$$\ln \frac{X_{ji}}{X_{jj}} = I_i - I_j + \theta v + \theta l + \theta c - \theta \ln \tau_{ji} - \theta O_j + \theta \kappa_{ji} \quad \forall j \neq i, \quad (5.35)$$

where κ_{ji} is an error term orthogonal to all other explanatory variables. To be able to capture potential reciprocity in geographic barriers, I use a variation of Eaton and Kortum (2002) and assume that this error term (with variance σ^2) affects two-way tourism such that the variance-covariance matrix of κ has nonzero off-diagonal²¹ elements $\mathbb{E}(\kappa_{ji}, \kappa_{ji}) = \sigma^2$. The procedure to obtain estimates of I_i is therefore to first estimate Equation 5.35 using OLS to obtain a set of residuals $\hat{\varepsilon}_{ji}$. The second step involves estimating $\theta^2 \sigma^2$ by averaging $\hat{\varepsilon}_{ji} \hat{\varepsilon}_{ij}$ using $((\hat{\varepsilon}_{ji} + \hat{\varepsilon}_{ij})/2)^2$ (Figure 5.3). In a final step, these parameter estimates of the variance-covariance matrix are used to estimate Equation 5.35 by feasible generalized least squares (FGLS). Table 5.4 contains the results.

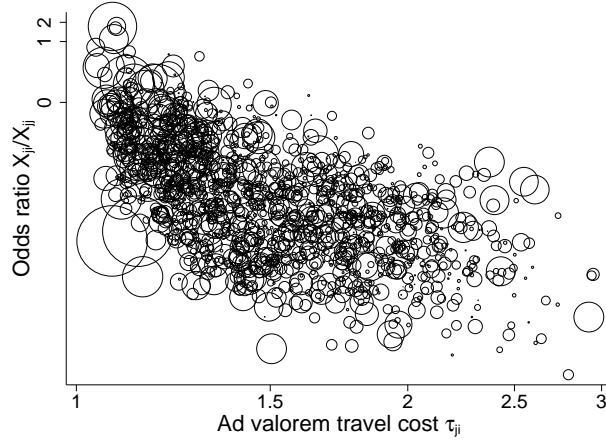


Figure 5.3: Parameter estimates of $\theta^2 \sigma^2$ of the reduced dataset comprising 41 countries. Circle areas represent the size of each weight $((\hat{\varepsilon}_{ji} + \hat{\varepsilon}_{ij})/2)^2$.

The estimates of the inbound tourism effect I_i indicate that the US is—relative to all other countries in the dataset—the most competitive country in 2014 in tourism, closely followed by the UK and China. Popular tourist destinations such as France, Brazil, Spain, Italy, Turkey, Thailand, Malaysia and Greece also obtain a relatively high and positive value of the competitiveness index I_i . Countries with relatively high unit labour costs in accommodation and food services—such as Switzerland, Ireland, Austria, Poland, Finland, and Belgium (OECD, 2017b)—are only moderately competitive, if at all. The least competitive countries are the ones where the tourism industry has not been fully developed (S_i and A_i are therefore relatively small in their value), such as Ghana, Kenya, Uganda, Bangladesh, Sri Lanka, Oman, Pakistan and Jordan. The mean centred 2015 TTCI of the respective countries is reported in column 5 and compares well to the estimates of the inbound tour-

²¹The diagonal elements of the variance-covariance matrix can be excluded as a result of the constraint $j \neq i$.

Table 5.4: Tourism competitiveness.

(1) Variable	(2)	(3)	(4)	(5)	(6) est.	(7)	(8) s.e.
Airfare			$-\theta$		-5.79		(0.28)
Visa restrictions			θv		0.03		(0.15)
Common language			θl		0.41		(0.07)
Colonial ties			θc		1.52		(0.14)
Country	Destination Country			TTCI	Origin Country		
		est.	s.e.			est.	s.e.
United States	I_1	2.38	(0.08)	0.86	$-\theta O_1$	2.30	(0.12)
United Kingdom	I_2	2.18	(0.11)	0.86	$-\theta O_2$	2.21	(0.18)
China	I_3	1.87	(0.11)	0.28	$-\theta O_3$	0.26	(0.25)
France	I_4	1.71	(0.13)	0.98	$-\theta O_4$	1.47	(0.16)
Brazil	I_5	1.47	(0.15)	0.11	$-\theta O_5$	0.87	(0.23)
Spain	I_6	1.47	(0.07)	1.05	$-\theta O_6$	1.19	(0.10)
Italy	I_7	1.45	(0.07)	0.72	$-\theta O_7$	1.09	(0.11)
Germany	I_8	1.39	(0.16)	0.97	$-\theta O_8$	0.35	(0.20)
Russian Federation	I_9	1.12	(0.09)	-0.18	$-\theta O_9$	0.52	(0.10)
Japan	I_{10}	1.08	(0.13)	0.68	$-\theta O_{10}$	0.71	(0.17)
Canada	I_{11}	1.01	(0.11)	0.66	$-\theta O_{11}$	1.72	(0.20)
Turkey	I_{12}	0.78	(0.10)	-0.18	$-\theta O_{12}$	-0.01	(0.18)
Thailand	I_{13}	0.73	(0.07)	0	$-\theta O_{13}$	0.77	(0.18)
Netherlands	I_{14}	0.52	(0.14)	0.41	$-\theta O_{14}$	1.43	(0.18)
United Arab Emirates	I_{15}	0.49	(0.11)	0.17	$-\theta O_{15}$	2.10	(0.17)
Malaysia	I_{16}	0.49	(0.15)	0.15	$-\theta O_{16}$	0.01	(0.25)
Switzerland	I_{17}	0.30	(0.08)	0.73	$-\theta O_{17}$	0.96	(0.14)
Greece	I_{18}	0.19	(0.07)	0.10	$-\theta O_{18}$	0.25	(0.13)
Austria	I_{19}	0.12	(0.12)	0.56	$-\theta O_{19}$	-0.25	(0.16)
Denmark	I_{20}	0.12	(0.13)	0.12	$-\theta O_{20}$	0.82	(0.21)
Korea (the Republic of)	I_{21}	0.04	(0.16)	0.11	$-\theta O_{21}$	0.41	(0.22)
India	I_{22}	-0.23	(0.14)	-0.24	$-\theta O_{22}$	-1.57	(0.24)
Egypt	I_{23}	-0.30	(0.24)	-0.77	$-\theta O_{23}$	-1.11	(0.31)
Philippines	I_{24}	-0.34	(0.11)	-0.63	$-\theta O_{24}$	-0.33	(0.15)
Poland	I_{25}	-0.36	(0.07)	-0.18	$-\theta O_{25}$	0.59	(0.17)
Nigeria	I_{26}	-0.43	(0.17)	-1.47	$-\theta O_{26}$	-0.62	(0.27)
Czech Republic	I_{27}	-0.47	(0.21)	-0.04	$-\theta O_{27}$	-0.23	(0.23)
Portugal	I_{28}	-0.55	(0.12)	0.38	$-\theta O_{28}$	-1.20	(0.23)
Ireland	I_{29}	-0.62	(0.18)	0.27	$-\theta O_{29}$	0.68	(0.22)
Norway	I_{30}	-0.62	(0.07)	0.26	$-\theta O_{30}$	-0.35	(0.17)
Belgium	I_{31}	-0.71	(0.11)	0.25	$-\theta O_{31}$	-0.07	(0.15)
Sweden	I_{32}	-0.84	(0.07)	0.19	$-\theta O_{32}$	-1.41	(0.14)
Finland	I_{33}	-1.26	(0.05)	0.21	$-\theta O_{33}$	-1.27	(0.09)
Ghana	I_{34}	-1.55	(0.17)	-1.25	$-\theta O_{34}$	-0.78	(0.27)
Kenya	I_{35}	-1.61	(0.08)	-0.68	$-\theta O_{35}$	-1.31	(0.15)
Uganda	I_{36}	-1.63	(0.16)	-1.15	$-\theta O_{36}$	-0.49	(0.25)
Bangladesh	I_{37}	-1.69	(0.17)	-1.36	$-\theta O_{37}$	-3.10	(0.30)
Sri Lanka	I_{38}	-1.82	(0.19)	-0.46	$-\theta O_{38}$	-1.77	(0.34)
Oman	I_{39}	-1.84	(0.09)	-0.47	$-\theta O_{39}$	-0.91	(0.23)
Pakistan	I_{40}	-2.04	(0.15)	-1.34	$-\theta O_{40}$	-3.22	(0.25)
Jordan	I_{41}	-2.09	(0.08)	-0.67	$-\theta O_{41}$	-0.73	(0.13)

Number of observations: 1,640

Notes: Estimated is Equation 5.35 by FGLS using 2014 data (see Appendix B). The parameter estimates are normalised to that $\sum_{i=1}^{41} I_i = 0$ and $\sum_{i=1}^{41} -\theta O_i = 0$. Standard errors are in parentheses. The table also displays the mean centred 2015 TTCI from WEF (2015) (the mean of the 41 countries listed is 4.26).

ism effect I_i . The majority of positive values of the I_i index are also positive in terms of the TTCI. Many countries also compare well in terms of the overall ranking (highest I_i - highest TTCI and vice versa).

The estimates of the outbound tourism effect O_j indicate that the US and the UK are the most diverse in terms of exploring foreign countries to undertake tourism activities, while Bangladesh and Pakistan are the least diverse.

As for bilateral preferences, common language and colonial ties remain prominent, while visa restrictions are not of importance (and therefore insignificant) in the reduced dataset of 41 countries. The price parameter obtains a value of $\theta = 5.79$.

5.6 Counterfactuals

This section quantifies the welfare gains from international tourism across countries using the gravity equation and structural models parameters thereof in counterfactual exercises. The exercises involve moving the economy to a new equilibrium without international tourism. The resulting changes in real income $W_j = Y_j^E / P_j^E$ are then associated with the gains from international tourism.

Because international tourism receipts may represent a large or a small share of a country's gross value of domestic output and therefore result into relatively small or relatively large changes in real income, the gains from tourism need to be quantified in a multi-sector equilibrium model. Crucial for quantifying the gains from tourism are therefore the expenditure share $\alpha_j = X_j / X_j^E$ as well as the output elasticity $\gamma_j = Y_j / Y_j^E$, as already illustrated by the theoretical framework outlined above. Accounting for the relative differences in α_j and γ_j ensures that the calculated gains from international tourism across countries can be compared against a common benchmark.

As in Arkolakis, Costinot and Rodríguez-Clare (2012), I start by considering a foreign price shock in country j which affects labour endowments $\mathbf{L} \equiv \{L_i\}$ and travel costs $\boldsymbol{\tau} \equiv \{\tau_{ji}\}$, but leaves unchanged country j 's labour endowment L_j and domestic travel costs τ_{jj} . Furthermore, I assume that this shock leaves unchanged a country's number of available activities $\mathbf{S} \equiv \{S_i\}$, individual characteristics $\mathbf{A} \equiv \{A_i\}$, and bilateral preferences $\mathbf{a} \equiv \{a_{ji}\}$. Formally

RESTRICTION 2: *A foreign price shock in the tourism sector in country j is a change from $(\mathbf{L}, \boldsymbol{\tau}, \mathbf{S}, \mathbf{A}, \mathbf{a})$ at time t to $(\mathbf{L}', \boldsymbol{\tau}', \mathbf{S}', \mathbf{A}', \mathbf{a}')$ at time $t + 1$ such that $L_j = L'_j$, $\tau_{jj} = \tau'_{jj}$, $\mathbf{S} = \mathbf{S}'$, $\mathbf{A} = \mathbf{A}'$, and $\mathbf{a} = \mathbf{a}'$, with $\mathbf{L} \equiv \{L_i\}$, $\boldsymbol{\tau} \equiv \{\tau_{ji}\}$, $\mathbf{S} \equiv \{S_i\}$, $\mathbf{A} \equiv \{A_i\}$, and $\mathbf{a} \equiv \{a_{ji}\}$.*

In other words, foreign price shocks correspond to any changes in foreign labour endowments and international travel costs that leave everything else unchanged, including country j 's labour endowment, domestic travel costs, and all economic activity not related to tourism.

As is standard in the related literature²², country j 's overall consumer price index P_j^E in a two-sector economy is given by

$$P_j^E = \left(P_j\right)^{\alpha_j} \left(P_j^0\right)^{1-\alpha_j}.$$

Sector 0 combines all economic activity not related to tourism. Combining this expressions with the definition of income given by Equation 5.17, real income can be written as

$$W_j = L_j (w_j)^{\gamma_j} \left(w_j^0\right)^{\gamma_j^0} (P_j)^{-\alpha_j} \left(P_j^0\right)^{-\alpha_j^0}.$$

As only the tourism sector is subject to foreign price shocks in the counterfactual equilibrium by R2, and using labour L as the numeraire, this expression reduces to

$$\widehat{W}_j = (\widehat{w}_j)^{\gamma_j} \left(\widehat{P}_j\right)^{-\alpha_j} \quad (5.36)$$

where $\widehat{v} \equiv v'/v$ denotes the change in any variable v between the initial and the new equilibrium (indexed with a prime). To be able to evaluate the changes in real income therefore, one needs to keep track of the changes in prices (Step 1) as well as the changes in income (Step 2 in the Appendix B.1).

As is standard in the macroeconomics literature, the thought experiment of moving to autarky provides insight into the total gains from tourism. In autarky, a country's domestic consumption equals its domestic output of all tourism activities. Output levels result from the optimum allocation of resources to economic activities, given employment and the exogenous preference parameters.

To evaluate the welfare gains from international tourism, I move to a new equilibrium where all countries impose infinitely high visa restrictions. For notational simplicity, I assume that these visa costs are measured in terms of iceberg travel costs τ_{ji} . Similar to the case of autarky in international trade, I consider the visa costs in the new equilibrium in international tourism to be $\tau'_{ji} = +\infty$ for any pair of countries $j \neq i$.

PROPOSITION 1: *Suppose that R1 and R2 hold. Then the change in real income associated*

²²For example Costinot and Rodríguez-Clare (2014), Donaldson (2010), Costinot, Donaldson and Komunjer (2012), Anderson and Yotov (2010), and Chaney (2008).

with moving to autarky in country j can be computed as

$$\widehat{W}_j^A = \underbrace{\left(\frac{X_j}{Y_j}\right)^{\frac{(\gamma_j - \alpha_j)}{1 - \gamma_j}}}_{\text{change in income}} \underbrace{(\lambda_{jj})^{-\alpha_j/\epsilon}}_{\text{change in prices}} \quad (5.37)$$

Proof: See Appendix B.1.

The welfare formula to quantify the gains from tourism consists of two components: the left factor quantifies the changes in tourism income as a result of changes in overall tourism demand (consisting of domestic and international tourism), the right factor quantifies the changes in prices as a result of substituting international tourism with domestic tourism activities.

The right factor is structurally equivalent to the standard welfare formula in international trade, as first demonstrated by Eaton and Kortum (2002) and generalised by Arkolakis, Costinot and Rodríguez-Clare (2012). It builds on the intuition of the demand elasticity, which links changes in the factor proportions λ_{ji} and λ_{jj} , with changes in foreign and domestic prices. From the market clearing condition, and because budget shares need to sum to one, a drop in foreign expenditure λ_{ji} must correspond to an increase in domestic expenditure λ_{jj} , the extent of which is measured by the demand elasticity ϵ . Given the definition of the demand elasticity however, these changes can also be associated with changes in prices, as illustrated by the right factor in Equation 5.37. The occurrence of the expenditure share α_j in this factor ensures that changes in prices only materialises into overall changes in the consumer price index to the extent tourism spending relative to overall spending occurs in the economy.

The left factor of Proposition 1 is new to the macroeconomics literature in that it accounts for the changes in income from tourism, given by $Y_j^E = L_j(w_j)^{\gamma_j}$. Using labour as the numeraire, this expression reduces to $\widehat{Y}_j^E = (\widehat{w}_j)^{\gamma_j}$. In a subsequent step it can be shown that changes in wages are determined by $\widehat{w}_j = (X_j/Y_j)^{1/(1-\gamma_j)}$ in autarky (see Appendix B.1). The fraction X_j/Y_j therefore defines the level of changes in income. The intuition derives from the definition of income and spending. Total income from tourism Y_j consists of domestic (Y_{ii}) and international ($Y_j^{\text{int'l}} = \sum_{j \neq i}^I X_{ji}$) tourism receipts. Total expenditure in tourism X_j consists of domestic (X_{jj}) and international tourism spending ($X_j^{\text{int'l}} = \sum_{i \neq j}^I X_{ji}$). The share of tourism expenditure relative to tourism income can therefore be rewritten as

$$\frac{X_j}{Y_j} = \frac{Y_j - Y_j^{\text{int'l}} + X_j^{\text{int'l}}}{Y_j} = 1 + \frac{\text{Tourism deficit}}{\text{Tourism output}}, \quad (5.38)$$

where $X_j^{\text{int'l}} - Y_j^{\text{int'l}}$ is the tourism deficit, given by the difference of international tourism

spending and international tourism receipts. In autarky therefore, tourism output changes by the amount of the tourism deficit. If international tourism expenditure is larger than the amount of international tourism receipts ($X_j^{\text{int'l}} > Y_j^{\text{int'l}}$), a country's income from tourism will increase in the autarky case. This is because tourism income in autarky (consisting of $Y_{jj} + X_j^{\text{int'l}}$) is larger than what it used to be ($Y_{jj} + Y_j^{\text{int'l}}$).

Having described the determinants of the level of changes in income, the scale of the changes in income is defined by the relative difference in the output elasticity²³ and expenditures share. If $\gamma_j > \alpha_j$, consumers benefit from higher income if $X_j/Y_j > 1$. If $\gamma_j < \alpha_j$ however, consumers loose from higher income if $X_j/Y_j > 1$, as in this case, the higher income materialises into higher prices (driven by the wage adjustment \widehat{w}_j) to an extent larger than consumers can benefit from higher income. The opposite is true however if total income from tourism decreases in autarky such that $X_j/Y_j < 1$. With $\gamma_j > \alpha_j$, this would lead consumers to benefit from less tourism output as a result of price reductions in the sector, which are larger than the reductions in income. Whether or not a tourism deficit leads to an increase or reduction in income can thus only be identified if relative income and spending in the sector are additionally taken into account.

Considering both, the left and the right factor of Equation 5.37, allows to quantify the changes in real income comprehensively as both the changes in income and the changes in prices are considered. Both factors are important. Some countries run large tourism deficits, resulting into a higher volatility with respect to changes in prices, while others are primarily dependent on international tourism receipts, resulting into a higher volatility with respect to changes in income. In either case, the changes in real income are predicted sufficiently accurately by Proposition 1. Using the data described in Section 5.3 and an outbound tourism demand elasticity of $\epsilon = -4$ (see Table 5.1), the welfare gains from international tourism can be calculated using $G_j = 1 - \widehat{W}_j^A$. Table 5.5 contains an overview of the results; Table B.3 contains the results of all of the 135 countries analysed.

Depending on a country's income from international tourism, the tourism deficit, and the relative size of the tourism sector, the gains from international tourism²⁴ range from 0.03% for Sierra Leone, to 0.19% for the US, to 54% for the Maldives.

For Sierra Leone and the US, domestic tourism contributes significantly to gross tourism output (indicated by a high value of λ_{jj}). The gains from international tourism due to

²³It should be noted that the output elasticities $\gamma_j = Y_j/Y_j^E$ are determined endogenously. That is, in the new partial equilibrium, they actually take the value $\gamma_j = Y_j'/Y_j^{E'} = X_j/(X_j + Y_j^0)$, as all spending must be equivalent to all economic output in autarky. As tourism spending is much smaller than tourism income for many countries, the gains from tourism can however only be quantified by leaving the output elasticity in moving from the initial to the new equilibrium unchanged.

²⁴Faber and Gaubert (2016) calculate the gains from international tourism for Mexico to be 2.43% using a tourism trade elasticity of 1.7. The results I obtain for Mexico are significantly lower (0.17%), as a result of higher absolute value of the demand elasticity (4), and the scaling of the tourism sector to the entire economy using income and expenditure shares.

lower prices of activities consumed elsewhere are therefore small. In addition, for both countries, the tourism deficit is close to zero (indicated by an approximate unit value of X_j/Y_j). The gains from international tourism in terms of income are therefore small. The tourism sector also plays a relatively unimportant role in both country's gross value of domestic output (indicated by a low value of γ_j). Jointly, the relatively low demand in international tourism combined with a small tourism deficit and a relatively small size of the tourism sector result into marginal to no gains from international tourism.

At the other extreme, the gains from international tourism can be large if X_j/Y_j takes a relatively small and γ_j a relatively large value. For the Maldives, almost all income from tourism is generated by international tourism (indicated by a small value of X_j/Y_j). Furthermore, the economy is largely dependent on the tourism sector (indicated by a high value of γ_j). Jointly, the relatively high economic importance of international tourism combined with a relatively large size of the tourism sector result into significant to extremely large gains from international tourism.

Another view on the gains from international tourism can be obtained by classifying the countries by their level of development. Table 5.5—which is rank ordered by the size of the gains from international tourism—shows that the countries with the highest gains from international tourism are small island developing states (SIDS, indicated by a ‡). This result is striking as five out of the first ten countries by gains from international tourism are SIDS (noting however that the list of countries in Table 5.5 is a nonexhaustive list). SIDS gain significantly from international tourism due to their disproportional high income from and dependency on the international tourism sector. Developing countries (indicated by a *) on the other hand seem to be evenly distributed across the entire table. Large gains are obtained for many developing countries, which are also popular tourist destinations such as Jamaica and Thailand, due to the significant contribution of international tourism to the national economy (see Table B.3). Small gains are obtained for developing countries with large tourism deficits such as China and Brazil.

It should be noted that the results calculated in this section strictly refer to the gains from *international* tourism. These are not to be confused with the *overall* gains from tourism, which include both the gains from domestic and international tourism. If international tourism spending is as high as international tourism receipts, the gains from international tourism are insignificant (conditional on the gains due to lower prices however), whereas the overall gains from tourism may in many cases remain largely significant (e.g. due to a large domestic tourism sector).

Further, it should also be noted that Table 5.5 indicates that the range of the gains from international tourism (0.03-54%) is much larger than the range of the gains from international trade (1.5-8.1%, as calculated by Costinot and Rodríguez-Clare, 2014, for the majority of OECD countries using the Armington trade model). This is because of the

much higher variation of the relative size of the tourism sector across countries, as indicated by the large variation in the level of the output elasticity γ_j .

Table 5.5: Gains from international tourism.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Country	X_j/Y_j	λ_{jj}	α_j	γ_j	$\widehat{W}_{j,w}$	$\widehat{W}_{j,\lambda_{jj}}$	\widehat{W}_j
		[-]	[%]	[%]	[%]	[%]	[%]	[%]
1	Maldives‡	0.12	19	3.5	28.5	52.96	1.46	53.65
2	Fiji‡	0.18	53	1.9	11.0	15.84	0.31	16.10
3	Croatia	0.23	69	2.7	11.5	13.67	0.25	13.89
4	Cambodia*	0.31	56	3.9	13.2	11.90	0.56	12.39
5	Montenegro	0.24	71	2.1	9.4	10.99	0.18	11.15
6	Belize‡	0.27	58	2.7	10.2	10.26	0.37	10.59
7	Kuwait*	3.53	25	7.9	1.7	7.59	2.73	10.11
8	Bahamas‡	0.32	65	3.3	11.0	9.37	0.36	9.69
9	Jordan*	0.30	32	2.0	7.2	6.58	0.56	7.10
10	Jamaica‡*	0.36	55	2.9	8.9	6.47	0.44	6.88
⋮								
71	Gambia*	0.58	42	1.1	2.0	0.48	0.25	0.73
72	Vietnam*	0.68	74	2.7	3.9	0.48	0.21	0.69
73	Uruguay*	0.91	42	2.9	3.3	0.03	0.64	0.67
74	New Zealand	0.79	75	4.8	6.0	0.30	0.35	0.65
75	Sri Lanka*	0.74	51	2.2	3.0	0.27	0.37	0.63
76	Serbia	1.00	33	2.3	2.4	0.00	0.62	0.62
77	Germany	1.14	74	6.4	5.4	0.14	0.47	0.61
78	Switzerland	0.96	47	3.2	3.1	0.00	0.61	0.61
79	Netherlands	1.11	44	2.7	2.3	0.04	0.55	0.59
80	Sweden	1.12	58	3.9	3.4	0.06	0.52	0.58
⋮								
120	Ecuador*	0.83	54	1.3	1.6	0.05	0.19	0.25
121	Romania	1.07	55	1.5	1.4	0.01	0.23	0.24
122	Mozambique*	1.12	66	2.5	2.6	-0.02	0.25	0.23
123	Kazakhstan	1.08	67	1.8	1.5	0.02	0.18	0.20
124	Malawi*	1.18	77	2.4	2.2	0.03	0.16	0.19
125	United States	0.91	85	3.6	4.0	0.04	0.14	0.19
126	Sudan*	0.83	84	2.1	2.6	0.09	0.09	0.19
127	Mexico*	0.97	90	6.3	6.5	0.01	0.16	0.17
128	Indonesia*	0.97	78	2.6	2.7	0.00	0.16	0.16
129	Chile*	0.97	83	3.3	3.4	0.00	0.15	0.15
130	Pakistan*	1.11	83	2.9	2.7	0.02	0.14	0.15
⋮								
135	Sierra Leone*	0.92	82	0.4	0.5	0.00	0.02	0.03

Notes: Small island developing states indicated by a ‡. Developing countries indicated by a *.

As most of the international tourism is dependent on long-distance international air transport, the results in Table 5.5 can also be indirectly linked with aviation's socio-economic contribution and impact. Vice versa, as the gains from international tourism are directly related to a country's dependency on international tourism, they are also informative towards determining the potential welfare impacts associated with any type of policies in this sector. For example, the results in Table 5.5 indicate that the recent policy agreement of the International Civil Aviation Organization (ICAO, 2016) to stabilise aviation's CO₂ emissions to 2020 levels through carbon offsetting would inevitable be discriminating

against SIDS. Fortunately, the current scheme is designed to exempt SIDS (among others) from participation, unless they volunteer to decide to do so.

5.7 Summary

This chapter provides intuition towards relating a consumer's preference to travel to foreign countries to undertake activities. It then applies these preferences to a macroeconomic framework featuring absolute and comparative advantage across a continuum of activities consumed in locations worldwide to describe international tourism flows in a basic Ricardian sense. The resulting system of equations determines price levels, budget shares and wages and is shown to be observationally equivalent to the standard gravity equation in international trade, featuring bilateral accessibility and multilateral resistance terms.

Comparative advantage facilitates, while geographic barriers inhibit potential gains from international tourism. Tourism falls unequivocally and more elastic with distance due to higher prices and information barriers. Speaking the same language and colonial ties both attenuate these barriers, which are in some cases even compensating for the additional cost of visa restrictions.

The global phenomenon of tourism can to some extent also be attributed to common preferences in activities. The results obtained in this chapter indicate that the search for variables explaining common preferences in activities may prove to be successful in explaining global tourism patterns.

A country's comparative advantage adjusted for its labour costs provides insight into a country's competitiveness as a tourism service provider. The gravity equation can be used as a tool to quantify the tourism competitiveness across countries. The obtained indexes compare well to the well-established Travel and Tourism Competitiveness Index of the World Economic Forum.

The welfare gains from international tourism predominantly depend on (i) the size of the tourism sector in each country and on (ii) the contribution of international tourism to this sector, and range from 0.03% for Sierra Leone, to 0.19% for the US, to 54% for the Maldives. While developing countries may either have a high or a low dependency on international tourism, the majority of SIDS are found to have a disproportional high income from and thus dependency on it.

Chapter 6

International trade and tourism in a CO₂-constrained world

This chapter builds on theory-consistent, multi-country gravity models of international trade and tourism and uses comparative static exercises to show the welfare implications associated with environmental policies in international sea and air transport. This chapter therefore combines the international trade model from Chapter 4 and the international tourism model from Chapter 5 into a model of the global economy and jointly describes column 2 well as column 3 of Table 1.1.

The analysis in this chapter builds on comparative-dynamic exercises in a Computable General Equilibrium (CGE) framework to show the welfare implications associated with cost increases in international transport, by linking a theoretical framework of consumer demand with a theoretical framework of transport supply.

Consumers in each country maximise their utility from the consumption of goods and activities from the industry and tourism sectors. Industry production and consumption involves goods trade. Tourism service output and consumption involves international tourism. On the supply side, countries produce goods and services using only labour. The export of goods and travel of tourists to foreign countries is accomplished by international sea and air transport.

In equilibrium, supply equals demand. Introducing a price on the CO₂ emitted in international transport will result into foreign price shocks and therefore into macroeconomic imbalances. By solving for a new equilibrium state in which these price shocks are taken into account, one can determine the changes in real income in each country associated with the introduction of carbon emissions pricing schemes in the international maritime and air transport industry.

6.1 Theoretical framework

The mathematical derivations used to describe the theoretical framework of trade, tourism, and international transport involve the transfer of supply-side related changes in transport costs to demand-related changes in prices in three main parts.

The first part specifies the gravity equations for international trade and tourism from Chapters 4 and 5 to link prices of goods and tourism activities to transport costs. International goods trade is limited to trade via sea transport. The trade model used in this chapter is therefore a simplified version of the trade model described in Chapter 4. International tourism is restricted to international tourism via air travel. Both simplifications are a result of the underlying data limitations. They are however reasonable, considering that the realised model covers about 94% of all international transport related CO₂ as illustrated in Table 1.1.

The second part specifies a cost function of a representative transport firm that uses exogenous input prices (including fuel) to produce a certain level of transport output with a given technology and operational efficiency.

The third part then specifies the exogenously determined carbon price, which later takes the form of a bunker fuel levy (charged per tonne of fuel purchased for consumption), before trade and tourism demand are balanced with transport supply using equilibrium prices.

Setup. The model builds on a world economy comprising $i = 1, \dots, I$ potentially asymmetric countries and $h = 1, \dots, H$ economic sectors. The sectors considered are the industry (I), tourism (T), services, and international transport sectors. Industrial activity is related to goods trade; tourism activity to passenger travel. The service sector combines all economic activity other than those in the industry and tourism sectors. The international transport sector is comprised by the international maritime and aviation industry.

Labour L^h is the only factor input with wage $\mathbf{w} = \{w_i\}$. Country i 's total output is therefore given by $Y_i = w_i \cdot L_i$, where $L_i = \sum_{h \in H} L_i^h$. In comparison to all other sectors, the number of workers in the international transport sector is small and insignificant and therefore ignored. The service sector is the catch-all labour category and includes all workers who are neither employed in the industry nor in the tourism sector. This sector is therefore immune to exogenous price shocks from international transport and will remain unchanged in the counterfactual exercises below.

Index notation relates the variables of economic activity to either the industry or tourism sector. Irrespective of the type of macroeconomic activity (trade or tourism), country j refers to the reporting country and country i to the partner country. The order of

the indices of each variable indicates if the variable is related to international trade or tourism activities using the concept of the direction of flow between the reporting and partner country. For example, if country j engages in international trade with country i , its expenditure X on imports from country i is denoted X_{ij} . If country j engages in international tourism with country i , its outbound tourism expenditure on country j is denoted X_{ji} . Using the index notation ij therefore denotes trade flows whereas the index notation ji denotes tourism flows.

Supply heterogeneity. Partner countries differ in terms of their production costs due to differences in labour—with factor income (wage) denoted as w_i —and supply capacity $\mathbf{S}_i \equiv \{z_i, N_i, f_i^e, A_i\}$. \mathbf{S}_i consists of all attributes other than labour, which make country i attractive as a supplier and/or destination country. It includes labour productivity¹ (z_i), the number of firms and the number of tourism activities in each country (N_i), sunk entry costs² (f_i^e), as well as other country-specific variables and attributes³ (A_i). Fixed costs differ across countries but do not vary between countries. Firms in each country are therefore confronted with increasing returns to scale (IRS) in production but constant returns to scale (CRS) in international transport.

Taken together, \mathbf{S}_i comprehensively describes country i 's "capacity" to become a partner for country j , in terms of international trade as well as in terms of international tourism. As \mathbf{S}_i will be assumed to remain constant between the initial and the new (environmentally constrained) equilibrium of the world economy, a precise definition of the attributes in \mathbf{S}_i is not required.

Transport costs. International trade and tourism involve the transport of goods from country i to country j (trade), or the transport of passengers from country j to country i (tourism). The expenses related to these transport services are denoted with f_{ij} and f_{ji} respectively. To comply with the multiplicative form of gravity however, these costs are measured in units of the one plus the ad valorem price equivalent of supply prices w_i

$$\tau_{ij} = 1 + f_{ij}/w_i \geq 1, \tau_{ji} = 1 + f_{ji}/w_i \geq 1, \quad (6.1)$$

where

$$(a) \tau_{jj} = 1, \tau_{ii} = 1, \text{ and}$$

¹The term productivity essentially describes a firm's total factor productivity (TFP). For manufacturing trade with no other inputs than labour, TFP reduces to labour productivity. For non-manufacturing trade, TFP includes inputs such as the quantity of arable land and natural resources (see e.g. Costinot, Donaldson and Smith, 2016).

²I consider producing firms in country i to be homogeneous with respect to the marginal and fixed costs of production as in e.g. Melitz and Redding (2015). In order to produce, firms face a sunk entry cost and draw an exogenous productivity from a degenerate productivity distribution. Due to the presence of fixed costs, only firms drawing a productivity z_i find it profitable to produce.

³In terms of tourism, countries differ in terms of their attractiveness as a destination country A_i (including climatic, geographic, historical, and cultural characteristics), factor inputs (w_i), and the number of available activities (reflecting a country's state of the tourism sector)

(b) $\tau_{ij} \leq \tau_{il} \cdot \tau_{lj}$, and $\tau_{ji} \leq \tau_{jl} \cdot \tau_{li}$ for any third country l .

Part *a* of Equation 6.1 states the domestic transport costs are zero. Part *b* of 6.1 rules out cross-country arbitrage opportunities and restricts tourism travel to flights via direct routes only.

Market structure. The prices faced by consumers in country j for goods imports from country i and for tourism activities consumed in country i are a constant markup over marginal cost

$$p_a(z_i) = m w_i \tau_a / z_i, \quad (6.2)$$

where $a = \{ij, ji\}$ denotes the type of activity and $m \geq 0$ the markup. The market structure is either characterised by monopolistic competition ($m > 0$) or perfect competition ($m = 0$).

Consumers (including firms) of internationally traded goods therefore pay the price of the good at the factory gate w_i/z_i , plus the expenses related to shipping those goods from the producing country to the importing country, given by τ_{ij} . The marginal cost of producing the quantities $Q \equiv \{q_i\}$ by a representative firm in country i using productivity z_i is therefore given by $w_i q_j(\omega)/z_i$, where $\omega \in \Omega$ denotes the type of good consumed.

Consumers of worldwide tourism activities pay a price $p_i \equiv w_i$ for the activity they carry out in location $l \in i$ (inclusive of lodging, food, services, etc.) and the expenses associated with travelling to location $l \in i$, given by τ_{ji} , both of which are sold or offered for sale at a lump-sum price. The marginal cost of the activities $S \equiv \{s_i\}$ in country i consumed by tourists from country j is therefore given by $w_i s_j(\omega)$, where $\omega \in \Omega$ refers to the type of activity consumed.

Expenditure functions (gravity). Consumers in each country purchase goods and activities in amounts $q(\omega)$ and $s(\omega)$ to maximise a CES objective. Their overall expenditure in each sector is given by⁴

$$X_a^h = \left(w_i^h \tau_a^h \right)^{\epsilon^h} X_j^h \left(P_j^h \right)^{-\epsilon^h} \mathbf{S}_i, \quad \text{where } a = \{ij, ji\}, \quad (6.3)$$

and with ϵ as the price elasticity of demand. X_{ij} therefore refers to country j 's total spending on goods imported from country i , whereas X_{ji} refers to country j 's total spending on tourism activities in country i . The CES price index P_j is given by

$$P_j^h \equiv \left(\sum_{i=1}^I \left(w_i^h \tau_a^h \right)^{\epsilon^h} \mathbf{S}_i \right)^{1/\epsilon^h}, \quad \text{where } a = \{ij, ji\}, \quad (6.4)$$

⁴See Chapters 4 and 5, and in particular Equations 4.29 and 4.4 for trade and Equations 5.11 and 5.10 for tourism

and summarises how prices (w_i^h) around the world, supply capacity around the world (\mathbf{S}_i) and geographic barriers (τ_a^h) govern prices in country j and lead to deviations from purchasing power parity.

For all sectors combined, country j 's aggregate consumer price index is given by

$$P_j = \prod_{h=1}^H \left(P_j^h\right)^{\alpha_j^h} \quad \text{where} \quad \sum_{h=1}^H \alpha_j^h = 1. \quad (6.5)$$

To be compliant with the gravity structure imposed by 6.3, the price elasticity of demand ϵ is defined as the proportionate change in factor proportions X_{ij} and X_{jj} , and X_{ji} and X_{jj} respectively

$$\epsilon^h \equiv 1 - \sigma = \frac{\partial \ln \left(X_a^h / X_{jj}^h \right)}{\partial \ln \tau_a^h}, \quad \text{where} \quad a = \{ij, ji\}. \quad (6.6)$$

In international trade, ϵ refers to the partial elasticity of relative imports with respect to transport costs (or prices respectively, with ϵ being the "Armington" elasticity) and X_{jj} to the value of goods produced in country j and also consumed in country j . In international tourism, ϵ refers to the partial elasticity of relative outbound tourism spending with respect to international travel costs and X_{jj} to domestic tourism spending i.e. the total spending of tourists choosing their home country as their destination country ($i = j$) to undertake activities.

Market clearing. Assuming that markets in each sector and country at the macro level clear ensures that aggregated supply and demand are consistent with a country's total output Y_i^h and expenditure X_j^h in each sector (see Chapters 4 and 5) such that

$$Y_i^h \equiv \sum_j X_a^h, \quad X_j^h \equiv \sum_i X_a^h, \quad \text{where} \quad a = \{ij, ji\}, \quad (6.7)$$

where $Y_i^h = w_i^h L_i^h$ is the value of production in sector h , and X_j^h is spending in sector h . Both values Y_i^h and X_j^h are inclusive of a country's spending in its home market (X_{jj}). Sector spending relative to total spending is thus determined by $\alpha_j^h \equiv X_j^h / X_j$.

Cross-sector substitutions and spillover effects are not accounted for. The former is negligible as the considered price changes are small. The latter may however be quantitatively important for remote countries such as SIDS. Trade also consists of traded tourism goods. Both sectors are therefore interlinked through goods trade. However, no spillover effects of changes in tourism demand on trade demand are accounted for in the model.

Budget shares across countries in each sector are given by

$$\lambda_a^h \equiv X_a^h / X_j^h, \quad \text{where} \quad a = \{ij, ji\}. \quad (6.8)$$

To comply with structural gravity on the one hand (Head and Mayer, 2014) and ensure internal consistency of the model on the other (see counterfactuals below), the following two conditions must hold:

1. Budget shares are independent of country j 's factor income w_j and therefore remain multiplicatively separable (proof see counterfactuals below).
2. Budget shares sum to one, i.e $\sum_{i=1}^I \lambda_a^h \equiv 1$, $a = \{ij, ji\}$, and therefore ensure that the market clearing condition given by Equation 6.7 holds.

A country's total income from all sectors is given by

$$Y_i = w_i L_i \equiv L_i \prod_{h=1}^H \left(w_i^h \right)^{\gamma_i^h}, \quad (6.9)$$

where $\gamma_i^h = Y_i^h / Y_i$ is country i 's endogenous output elasticity in sector h .

A country's total expenditure in all sectors is given by

$$X_i \equiv \sum_h X_i^h + D_i^h, \quad (6.10)$$

where D accounts for any deficits in trade and tourism. Adopting the specification of Head and Mayer (2014), these deficits are assumed to be exogenously given on a per capita basis in each sector $\sum_h D_i^h = D_i = L_i d_i$. The model is closed using

$$X_i = w_i L_i (1 + d_i). \quad (6.11)$$

Transport supply. Firms involved in the transport of goods and passengers use factor inputs (including fuel) to produce optimum levels of transport output (given prices), measured in either tonne-kilometres [t.km] or passenger-kilometres [p.km]. In doing so, transport firms continuously employ short-run cost-minimisation routines⁵ with respect to variable (fuel, labour, material) and fixed inputs (capital). Their cost function⁶ ζ is given by

$$C_\tau = \zeta(y, \boldsymbol{\vartheta}, \mathbf{P}, F, \xi(t)), \quad (6.12)$$

where C_τ refers to the variable costs a transport firm faces (at time t) to produce transport output y , $\boldsymbol{\vartheta} = [\vartheta_1, \vartheta_2, \dots, \vartheta_q]$ is a vector of output related quality differentials (e.g. average

⁵The relationship between optimum levels of exogenous factor inputs and output quantity is captured by a production function. Yet, the dual problem to maximising output s.t. a budgetary cost constraint is to minimise costs s.t. a budgetary production level constraint. Optimum levels of inputs can therefore also be found by specifying a cost function instead of a production function. And as the link between a theoretical framework of consumer demand with transport supply is accomplished through changes in prices as a result of variations in cost, I choose to adopt a cost function.

⁶For specifications of variable cost functions of transport firms see e.g. Caves, Christensen and Tretheway, 1984, Gillen, Oum and Tretheway, 1990, and Oum and Yu, 1998 for air transport and De Borger and Nonneman, 1981 and Tolofari, Button and Pitfield, 1986 for sea transport.

load factor, utilisation, and trip length), $\mathbf{P} = [P_{\text{fuel}}, P_{\text{labour}}, P_{\text{material}}, \dots, P_k]$ is a vector of variable, exogenous factor input price indices (including a price index for fuel), F denotes exogenous factor inputs which are treated as fixed in the short run (e.g. capital costs), and $\xi(t)$ is a general index of pure technical change.

Assuming CRS in international transport (considering the large number of available shippers, charterers, and airlines), the cost function can be transformed into a marginal cost function by dividing the firm's total costs by its total transport output

$$\frac{C_\tau}{y} = \zeta(\boldsymbol{\vartheta}, \mathbf{P}, F, \xi(t)). \quad (6.13)$$

Internalisation of externalities. The class of carbon emissions pricing schemes considered have in common the introduction of an (exogenously determined) price per unit of CO₂ released (a carbon price) to reduce and/or limit the amount of CO₂ emitted. As the release of CO₂ is directly related to the amount of fuel burned in the consumption process via an emissions factor, the carbon costs a transport firm faces under carbon emission pricing schemes can be expressed in units of the amount of fuel consumed

$$\text{carbon cost} \left[\frac{\$}{\text{t fuel}} \right] = \text{CO}_2 \text{ emissions factor} \left[\frac{\text{tCO}_2}{\text{t fuel}} \right] \times \text{CO}_2 \text{ price} \left[\frac{\$}{\text{tCO}_2} \right].$$

In other words, the costs associated with the release of CO₂ can be expressed as a fuel price surcharge. Under a carbon emissions pricing scheme, the overall fuel-related price a transport firm faces therefore amounts to

$$P_{\text{fuel}} = P_{\text{fuel(oil)}} + \eta_f P_{\text{CO}_2}, \quad (6.14)$$

where $P_{\text{fuel(oil)}}$ is the petroleum-based fuel price (without environmental surpluses), η_f is the fuel-related CO₂ emissions factor (which is assumed to be common to all sectors), and P_{CO_2} is the carbon price.

Similar to the transformation of international transport costs in trade and tourism, and to remain compliant with the multiplicative form of the gravity equations and transport cost function, the carbon costs ηP_{CO_2} are transformed into "iceberg carbon costs" using

$$P_{\text{fuel}} = P_{\text{fuel(oil)}} \underbrace{\left(1 + \frac{\eta_f P_{\text{CO}_2}}{P_{\text{fuel(oil)}}} \right)}_{\chi}, \quad (6.15)$$

where $\chi \geq 1$ is the one plus the CO₂ tax equivalent of net fuel prices.

Conditional on the level of transport output y , the amount of CO₂ released by both the

international maritime and air transport industry can be calculated using

$$\text{CO}_2 = \sum_{h=1}^H \eta_y^h \kappa^h \underbrace{\sum_{i=1}^I \sum_{j=1}^I Q_a^h D_a^h}_{\text{t.km, p.km}}, \quad a = \{ij, ji\}, \quad (6.16)$$

where η_y is an emissions factor related to total transport output y , measured either in tonnes of CO_2 per tonne-kilometre [$\text{tCO}_2/\text{t.km}$] or tonnes of CO_2 per passenger-kilometre [$\text{tCO}_2/\text{p.km}$]. κ^h accounts for return trips⁷ as the macro-theoretical framework (gravity) only accounts for flows in one direction. In international trade, imported goods remain in the destination country. In international tourism however, tourists need to return back to their country of origin. The round-trip factor therefore takes a value of $\kappa^h = 2$ in international tourism and $\kappa^h = 1$ in international trade.

Turning back to the description of the variables in Equation 6.16, Q^h refers to the quantities of tonnes shipped (q_{ij}^I) or number of passengers transported (N_{ij}^T), and D_a is the distance between countries. Q^h times D_a^h therefore yields into transport output measured in either tonne-kilometres (t.km) or passenger-revenue-kilometres (p.km).

Total transport output of a transport firm (or transport work performed) is assumed to remain constant. It is given by

$$y = \sum_{h=1}^H s^h(Q^h) \kappa^h \sum_{i=1}^I \sum_{j=1}^I Q_a^h D_a^h \equiv \text{const.}, \quad a = \{ij, ji\}, \quad (6.17)$$

where $s^h(Q^h)$ refers to the firm's market share in sector h . Holding total transport fixed is helpful to be able to straightforwardly determine equilibrium prices as will be shown below.

The intuition behind Equation 6.17 is as follows. A reduction in the quantities shipped or number of passengers transported will force smaller transport firms to exit the market, thus leaving a higher market share s^h for the remaining transport firms. Jointly, and on an aggregate level, these changes are assumed to perfectly counterbalance any changes in transport output y .

Balancing trade and tourism demand with transport supply. Trade and tourism

⁷ κ^h could also be defined as the ratio of tonne-vehicle-kilometres to revenue-tonne-kilometres ($\kappa^h = \text{t.vkt}/\text{t.rkt}$) and passenger-vehicle-kilometres to passenger-revenue-kilometres ($\kappa^h = \text{p.vkt}/\text{p.rkt}$) to specifically account for average distance travelled empty (average allocative utilisation), average vehicle capacity (vehicle economies of scale), and average load factors (average payload utilisation) (see e.g. Gucwa and Schäfer (2013)). All these factors increase the amount of CO_2 per unit of transport output emitted, provided however that they are not already accounted for in the emissions factor η_y as in Equation 6.16.

demand are linked with transport supply using equilibrium prices

$$f_a^h \equiv m^h \frac{C_\tau^h(y, \boldsymbol{\vartheta}, \mathbf{P}, F, \xi(t))}{y^h} D_a^h, \quad a = \{ij, ji\}, \quad (6.18)$$

where f are freight rates or airfares respectively in units of [\$/t] or [\$/p], $m \geq 0$ is the markup that is assumed to equivalently apply to all country pairs⁸, and $C_\tau(\cdot)/y$ are marginal transport costs given by Equation 6.13 in units of [\$/t.km] or [\$/p.km] respectively.

From the consumer's perspective, transport takes the form of extended supply. From the transport carrier's perspective however, this extended supply takes the form of transport demand. The supply and demand models can therefore be linked using Equation 6.18.

Equation 6.18 is valid for any theoretical framework of consumer demand which incorporates transport as one additional element of economic supply. Yet, the usage of the term *transport costs* in this context may cause confusion, especially when dealing with a macroeconomic and microeconomic framework simultaneously. This is because on the demand side, freight rates and airfares are referred to as the additional costs faced by consumers in purchasing goods and activities, whereas on the supply side, freight rates and airfares are the prices charged by transport firms passed down the supply-chain to consumers.

Equation 6.18 also makes clear that any variables measuring transport costs in the macroeconomics literature are endogenous. This is because, by transport costs, the theoretical demand framework actually refers to transport prices, which are determined in a supply-demand equilibrium. As the consumption of goods and activities from foreign countries requires some form of transport, a change in consumer demand inevitably materialises into a change in transport demand. A change in transport demand on the other hand will lead the transport carrier to adjust their output and hence price (given by f) to a new cost-minimising solution. At the same time however, consumers will adjust their demand in response to an increase in the overall price of goods and services (p_τ), as a result of higher transport costs f . Changes in transport costs therefore also involve changes in prices as well as changes in demand. Given this endogeneity problem, determining the demand elasticity from transport costs in international trade and tourism should make use of instrumental variables techniques and appropriate instruments. In models used to predict changes in prices however—as is the case in this study—the endogenous treatment of transport costs in a supply-demand equilibrium is subject to the underlying modelling assumptions (see Equation 6.17).

⁸International transport services involve a number of firms, which makes the markup structure complex and non-transparent. The transport of goods by sea involves shipowners, charterers as well as shippers, all of which may use a different markup structure. In international air travel, the airline operating the flight may be part of a global alliance, which thus also influences its markup structure. These examples illustrate that the competitive product strategy of a transport firm on individual trade and tourism routes is difficult to analyse, partially also because of the lack of relevant but confidential pricing information.

This completes the description of the theoretical framework. The next section uses this framework to derive a general equilibrium model consisting of the industry, tourism, and international transport sectors.

6.2 General equilibrium model

This section describes a general equilibrium model that allows to investigate the welfare impacts associated with environmental policies in both the international maritime and aviation industry. Employing the theoretical model described in the previous section, this section uses counterfactual exercises to quantify the change in each variable of interest, by starting from the variables describing the demand for goods and activities at the micro level, and by continuing with the variables describing international trade and tourism as well transport supply at the macro level.

The data collected to measure asymmetries across countries (see Section 6.3) describes the world economy in general equilibrium. This state of the world economy is referred to as equilibrium initial state of the model at time t . Once price shocks in the form of carbon prices to the international transport sector are introduced, a new state of the general equilibrium needs to be determined. This state of the world economy is referred to as new equilibrium state of the model at a point in time $t + 1$. The movement from the initial to the new equilibrium occurs along a balanced transition path and only keeps track of the changes of the key variables of interest. These include transport costs, consumers prices, wages, as well as total income and expenditure in each country. Formally:

DEFINITION 1: *Exogenous price shocks due to a tax on the CO_2 released by the international maritime and air transport industries is a change of the world economy from its initial general equilibrium state at time t*

$$[P_{CO_2}, P_{fuel}, \mathbf{P}, F, y, \boldsymbol{\vartheta}, \xi(t), \chi, \mathbf{f}, \boldsymbol{\tau}, \mathbf{p}, \mathbf{P}, \mathbf{w}, \mathbf{Y}, \mathbf{X}, \mathbf{L}, \mathbf{D}, \mathbf{S}]$$

to a new general equilibrium state at time $t + 1$

$$[P'_{CO_2}, P'_{fuel}, \mathbf{P}', F, y, \boldsymbol{\vartheta}', \xi(t+1), \chi', \mathbf{f}', \boldsymbol{\tau}', \mathbf{p}', \mathbf{P}', \mathbf{w}', \mathbf{Y}', \mathbf{X}', \mathbf{L}', \mathbf{D}', \mathbf{S}']$$

such that

$$\mathbf{P} = \mathbf{P}', F = F', y = y', \tau_{jj} = \tau'_{jj}, \mathbf{L} = \mathbf{L}', \mathbf{D} = \mathbf{D}' \text{ and } \mathbf{S} = \mathbf{S}',$$

with $\mathbf{P} \equiv \{P_k \neq P_{CO_2}, P_{fuel}\}$, $\boldsymbol{\vartheta} \equiv \{\vartheta_q\}$, $\mathbf{f} \equiv \{f_{ij}^h, f_{ji}^h\}$, $\boldsymbol{\tau} \equiv \{\tau_{ij}^h, \tau_{ji}^h\}$, $\mathbf{p} \equiv \{p_{ij}^h, p_{ji}^h\}$, $\mathbf{P} \equiv \{P_i^h\}$, $\mathbf{w} \equiv \{w_i^h\}$, $\mathbf{Y} \equiv \{Y_i^h\}$, $\mathbf{X} \equiv \{X_i^h\}$, $\mathbf{L} \equiv \{L_i^h\}$, $\mathbf{D} \equiv \{D_i^h\}$, and $\mathbf{S} \equiv \{\mathbf{S}_i\}$.

The structural model parameters α^h , γ^h , and ϵ^h remain constant per definition.

In other words, after a change in the carbon price (P_{CO_2}), the model keeps track of changes in fuel prices (χ), technology uptakes and operational improvements of a transport firm ($\vartheta, \xi(t)$), and the prices of goods and tourism activities from foreign countries ($\mathbf{f}, \boldsymbol{\tau}, \mathbf{p}$) faced by consumers in country i , including their overall price index (P_i), income (Y_i) and spending (X_i). The model leaves unchanged the input prices to a transport firm other than fuel and fuel related taxes (P_{CO_2}, P_{fuel}, F), a transport firm's total output (y), as well as country i 's ability to serve its own market ($\tau_{jj} = \tau'_{jj}$), labour endowment (L_i), deficits (D_i) and supply capacity \mathbf{S}_i . For the general equilibrium model derived in this section therefore, there is no need to additionally keep track (and collect data) of the variables that are assumed to remain constant per Definition 1 as they cancel out in the counterfactual exercises. This will be shown below.

Leaving domestic transport costs unchanged ($\tau_{jj} = \tau'_{jj}$) complies with the international authority of and hence candidate policy designs of the ICAO and the IMO, to only tackle CO_2 from international transport activities.

Under the assumption of small price changes, the counterfactual exercises in this study are carried out by taking logs of the respective demand or supply equation, differentiating the equation with respect to prices (or costs respectively), and then integrating this expression between the initial (t) and the new equilibrium state ($t+1$). To ease notation, any variable indexed without a prime indicates the initial equilibrium state; any variable indexed with a prime the new equilibrium state. Furthermore, changes in any variable v between the initial and the new equilibrium are denoted $\hat{v} \equiv v'/v$.

In what follows, the demand and supply equations are one after another subject of this exercise (the details of which can be found in the mathematical appendix C.1), before combining them in the last section into a general equilibrium model that is representative for the entire world economy. In accordance with the sequence of how the theoretical framework was laid out, this section starts by deriving a counterfactual equilibrium of the demand equations, then continues by deriving the counterfactual equilibrium of the transport firm, before combining them both using the counterfactual equilibrium of the link between trade and tourism demand and transport supply. To be able to keep track of the welfare changes in moving from the initial to the new equilibrium, the last part of this section deals with the quantification of changes in real income, given by $W_j = Y_j/P_j$.

Trade and tourism demand. Combining the demand equations in 6.3, the definition of budget shares in 6.8, expenditure functions in 6.3, and the market clearing conditions in 6.11 and 6.9, one can obtain a general equilibrium model for each sector that leaves the vector of wages as the only variable to be determined.

PROPOSITION 1: *Small changes in wages in any country $i \in I$ associated with any exogen-*

ous price shocks satisfy

$$\hat{w}_i^h = \frac{1}{Y_i^h} \sum_j \frac{\lambda_a^h (\hat{w}_i^h \hat{\tau}_a^h)^{\epsilon^h}}{\sum_{i=1}^I \lambda_a^h (\hat{w}_i^h \hat{\tau}_a^h)^{\epsilon^h}} (\hat{w}_j^h)^{\gamma_i^h} X_j^h, \quad a = \{ij, ji\}. \quad (6.19)$$

Proof: see Appendix C.1.

After a change in iceberg transport or travel costs τ_a^h , Equation 6.19 can be solved iteratively to obtain a vector of relative changes in wages $\mathbf{w} \equiv \{w_i^h\}$ in sector h . Assuming that a country's relative change in *overall* income equivalently applies to the relative change in expenditure from all sectors, changes in income can be linked to changes in expenditure using $\hat{X}_i^h \equiv \hat{X}_i$. Market clearing then implies $\hat{X}_i^h = \hat{Y}_i = (\hat{w}_i^h)^{\gamma_i^h}$. Exposing 6.19 to changes in prices ($\hat{\tau}_a$) and iterating over the vector of wages to obtain a new equilibrium state of the model therefore also involves the quantification of a country's overall income $\hat{Y}_i Y_i = (\hat{w}_i^h)^{\gamma_i^h} Y_i$, overall expenditure $\hat{X}_i X_i = \hat{Y}_i X_i$, and budget shares

$$\hat{\lambda}_a^h \lambda_a^h = \frac{\lambda_a^h (\hat{w}_i^h \hat{\tau}_a^h)^{\epsilon^h}}{\sum_{i=1}^I \lambda_a^h (\hat{w}_i^h \hat{\tau}_a^h)^{\epsilon^h}} \text{ in the new equilibrium and for each sector.}$$

The quantification of these variables is crucial for determining the welfare impacts associated with transport policies as described further below.

Transport Supply. Transport supply is characterised by Equation 6.12. Under CRS and by Definition 1, changes in the marginal costs of a transport firm $\hat{C}_\tau / \hat{y} \equiv \hat{C}_\tau$ can be made dependent on changes in the fuel price index, technology uptakes, and operational adjustments. Formally:

PROPOSITION 2: *Small changes in variable transport costs of a transport firm associated with exogenous carbon price shocks satisfy*

$$\hat{C}_\tau^h = (\hat{P}_{\text{fuel}}^h)^{\lambda_{\text{fuel}}^h} \dot{\xi}_h \prod_{q_h=1}^{Q_h} (\hat{v}_q^h)^{\varepsilon_{\hat{v}}^{q_h}},$$

where \hat{P}_{fuel} measures the changes in fuel price, λ_{fuel} is the fuel cost share, $\dot{\xi} \equiv \xi(t+1)/\xi(t)$ is the rate of pure technical change, and \hat{v}_q are operational adjustments of the transport firm between a point in time t and $t+1$. Proof: see Appendix C.1.

Given that changes in the carbon price can be linked to changes in fuel prices using 6.14, the above expression can be adjusted to directly account for the changes in prices associated with a carbon emissions pricing scheme. Using Equation 6.15 and the fact that oil related fuel prices remain unchanged by Definition 1 ($P_{\text{fuel(oil)}} = P'_{\text{fuel(oil)}}$), changes in fuel prices are given by $\hat{P}_{\text{fuel}} = \hat{\chi}$. In moving from an unconstrained (without a price on CO_2) to an

environmentally constrained scenario (with a price on CO_2), changes in the iceberg CO_2 cost component are given by $\hat{\chi} = \chi'/1$. Using these observations in the expression above, the changes in the costs of a transport firm associated with a carbon emissions pricing scheme can be calculated using

$$\hat{C}_\tau^h = (\chi')^{\lambda_{\text{fuel}}^h} \dot{\xi}_h \prod_{q_h=1}^{Q_h} (\hat{\vartheta}_q^h)^{\varepsilon_{\vartheta}^{q_h}}. \quad (6.20)$$

Equation 6.20 is meaningful as it links changes in the carbon price with changes in technology and operational patterns within a given time period $(t+1) - t$. It therefore captures the transition dynamics of a transport firm that is confronted with higher fuel or carbon prices. Faced with these price increases, a transport carrier may therefore invest into new technology and operational efficiency in order to reduce the increase in fuel or carbon costs. Assuming that the investment costs of these measures remain relatively small in comparison to the overall (fixed and variable) capital costs of a transport firm, these measures generally lead into overall cost reductions. Jointly, the uptake of new technology and improvements in operational efficiency ($\dot{\xi} < 1$ and $\hat{\vartheta}_q < 1$) therefore offset any cost increases of a transport carrier (\hat{C}_τ) if confronted with a carbon price ($\hat{\chi} > 1$). The extent of which these cost reductions will materialise however depends on the carbon price itself. Equation 6.20 is therefore central to quantifying the increases in costs that will be passed on to the consumers in the form of price increases of goods and activities in international trade and tourism. Section 6.4 therefore describes in detail the policy design investigated in this study, which provides the link between the level of the carbon price and the level of technology uptake and efficient improvements under a carbon emissions pricing scheme.

Link of demand and supply. The last step involves applying Equation 6.18 to the counterfactual changes of moving from the initial to the new equilibrium. Under constant markups⁹ and with transport output y remaining unchanged by Definition 1, changes in freight rates and airfares can be calculated using

$$\hat{f}_a^h = \hat{C}_\tau^h, \quad a = \{ij, ji\}.$$

Furthermore, using the definition of iceberg transport costs in Equation 6.1, changes in equilibrium prices in each sector can be shown to be dependent on the share of transport costs in consumer prices f_a/p_a (see Appendix C.1 for the details). In particular:

PROPOSITION 3: *Small changes in equilibrium prices of transport supply and trade and*

⁹The assumption of a constant markups is realistic for busy trade and tourism routes, which are commonly served by a large number of transport firms, but unrealistic for less busy trade and tourism routes, which may be served by only a few transport firms if not by a single one. Because transport supply equals trade and tourism demand in market equilibrium, a country's bilateral expenditure on less busy trade and tourism routes is small relative to its expenditure on the busy ones, which therefore influences the overall welfare impacts in each country only marginally. The measurement error associated with the assumption of a constant markup in international transport should therefore remain within acceptable limits.

tourism demand satisfy

$$\widehat{w}_i^h \widehat{\tau}_a^h = \underbrace{\widehat{w}_i^h \left(1 - \frac{f_a^h}{p_a^h}\right)}_{\text{change in supply prices}} + \underbrace{\widehat{C}_\tau^h \left(\frac{f_a^h}{p_a^h}\right)}_{\text{change in transport costs}}, \quad a = \{ij, ji\} \quad (6.21)$$

where: $1 - \widehat{w}_i \widehat{\tau}_a$ = is the change in consumer prices,
 f_a/p_a = is the share of transport costs in consumer prices,
 $1 - \widehat{w}_i$ = is the change in wages, and
 $1 - \widehat{C}_\tau$ = is the change in transport prices

in each sector h .

The occurrence of the wage adjustment $1/\widehat{w}_i$ in 6.21 results from the fact that transport costs f_a are normalised by supply prices $p_i \equiv w_i$ using $\tau_a = 1 + f_a/w_i$. A change in w_i therefore changes the baseline to which iceberg transport costs are measured against. Changes in w_i therefore change the value of τ_{ij} , even if f_{ij} remains unchanged.

Aside of keeping track of the changes in wages, Equation 6.21 is easily implemented into the general equilibrium model as it only requires one statistic: the share of transport costs in consumer prices f_a/p_a , which can readily be calculated from trade and tourism statistics (see Section 6.3). It should be noted that this share is also the only bilateral variable in 6.21, as the changes in transport prices by a transport firm are assumed to equivalently apply to all trade and tourism routes as a result of the assumption of constant markups in the international transport sector.

Within the stated system boundaries, Equation 6.21 closes the model and links the theoretical models of consumer demand with the theoretical model of transport supply. Equations 6.19, 6.20 and 6.21 therefore jointly describe a reduced form of the world economy in general equilibrium that can be used to quantify the changes in real income associated with exogenous price shocks in international transport by

1. introducing a price shock to the international transport system through $\widehat{C}_\tau^h = (\chi')^{\lambda_{\text{fuel}}^h} \dot{\xi}_h \prod_{q_h=1}^{Q_h} (\vartheta_q^h)^{\varepsilon_{\vartheta}^{q_h}}$ and subsequently
2. solving for a new general equilibrium by iterating over the vector of changes in wages \widehat{w}_i^h given by

$$\widehat{w}_i^h = \frac{1}{Y_i^h} \sum_{j=1}^I \frac{\lambda_a^h \left(\widehat{w}_i^h \left(1 - \frac{f_a^h}{p_a^h}\right) + \widehat{C}_\tau^h \left(\frac{f_a^h}{p_a^h}\right) \right)^{\epsilon^h}}{\sum_{i=1}^I \lambda_a^h \left(\widehat{w}_i^h \left(1 - \frac{f_a^h}{p_a^h}\right) + \widehat{C}_\tau^h \left(\frac{f_a^h}{p_a^h}\right) \right)^{\epsilon^h}} \left(\widehat{w}_j^h \right)^{\gamma_i^h} X_j^h, \quad a = \{ij, ji\}. \quad (6.22)$$

Welfare. The welfare impacts in each country are measured in terms of changes in real income $\widehat{W}_j \equiv \widehat{Y}_j/\widehat{P}_j$. It is therefore necessary to keep track of the changes in income $Y_j = \sum_{h=1}^H Y_j^h$ as well as the changes in the price index $P_j = \prod_{h=1}^H (P_j^h)^{\alpha_j^h}$ to quantify the changes in real income associated with exogenous price shocks.

Given the definition of the price index in Equation 6.5, changes in real income are given by

$$d \ln W_j = d \ln Y_j - \sum_{h=1}^H \alpha_j^h d \ln P_j^h.$$

Futhermore, given that the consumer demand equations and budget shares in each sector are multiplicatively separable, changes in the price index can be shown to merely depend on the domestic expenditure shares, the demand elasticities, and wages in each sector. Formally:

PROPOSITION 4: *Small changes in the price index in any country $j \in I$ associated with any exogenous price shocks satisfy*

$$d \ln P_j^h = \frac{-d \ln \lambda_{jj}^h}{\epsilon^h} + d \ln w_j^h.$$

Proof: See Appendix C.1.

Using Equation 6.9 and labour L_j as the numeraire, changes in income can be calculated sector by sector using

$$Y_j = L_j \prod_{h=1}^H (w_j^h)^{\gamma_j^h} \iff d \ln Y_j = \sum_{h=1}^H \gamma_j^h d \ln w_j^h.$$

Changes in the price index and changes in income can then be combined to calculate changes in real income

$$\begin{aligned} d \ln W_j &= \sum_{h=1}^H \left[\gamma_j^h d \ln w_j^h + \left(\frac{\alpha_j^h}{\epsilon^h} \right) d \ln \lambda_{jj}^h - \alpha_j^h d \ln w_j^h \right] \\ d \ln W_j &= \sum_{h=1}^H \left[\left(\gamma_j^h - \alpha_j^h \right) d \ln w_j^h + \left(\frac{\alpha_j^h}{\epsilon^h} \right) d \ln \lambda_{jj}^h \right]. \end{aligned}$$

Integrating this expression between the initial and the new equilibrium reveals that changes in a country's welfare from all sectors can be calculated using

$$\widehat{W}_j = \prod_{h=1}^H \underbrace{\left(\widehat{w}_j^h \right)^{\left(\gamma_j^h - \alpha_j^h \right)}}_{\text{change in income (supply)}} \underbrace{\left(\widehat{\lambda}_{jj}^h \right)^{\alpha_j^h / \epsilon^h}}_{\text{change in prices (demand)}}. \quad (6.23)$$

If only one sector is subject to a carbon emissions pricing scheme, this expression reduces to $\widehat{W}_j^h = \left(\widehat{w}_j^h\right)^{\left(\gamma_j^h - \alpha_j^h\right)} \left(\widehat{\lambda}_{jj}^h\right)^{\alpha_j^h / \epsilon^h}$.

The right factor of Equation 6.23 measures the welfare change associated with changes in prices and has become the standard formula to quantify the gains from trade (which involves assuming autarky), as it generally holds for an important class of trade models (Arkolakis, Costinot and Rodríguez-Clare, 2012). The intuition of it derives from the definition of the demand elasticity in 6.6, stating that any increase in domestic expenditure (due to price increases on foreign goods and tourism activities) must correspond with a decrease in expenditure on foreign goods or tourism activities (and vice versa), the extent of which is measured by the demand elasticity ϵ in combination with domestic trade and tourism expenditure shares λ_{jj}^h .

The left factor of Equation 6.23 measures the welfare change associated with changes in income¹⁰ as described in detail in Section 5.6. If income (or output respectively) is higher than spending in sector h ($\gamma_j^h > \alpha_j^h$), any increase in wages $\widehat{w}_j^h > 1$ will result into welfare gains $\widehat{W}_j > 1$, as a result of higher income. The opposite is true however in the converse case. If income is lower than spending in sector h ($\gamma_j^h < \alpha_j^h$), any increase in wages $\widehat{w}_j^h > 1$ will result into welfare losses $\widehat{W}_j < 1$, as consumers are affected more by price increases within their own country, given by $\widehat{w}_j^h > 1$, as they are from higher income. This intuition also applies to the case of decreasing wages ($\widehat{w}_j^h < 1$) with inverted signs.

It should be noted that, if average spending is approximately similar to average income in each sector, $\gamma_j^h - \alpha_j^h$ approaches zero and the gains or losses in terms of wages approach unity. This is the case in international trade if trade deficits are small (given by imports minus exports), and the case in international tourism if the tourism balance approaches zero (given by the inbound minus outbound tourism expenditure). For many countries therefore, the welfare changes in terms of income will be smaller than the welfare changes in terms of prices. Furthermore, as the tourism sector is smaller in comparison to the industry sector in many countries, γ_j^T as well as α_j^T will be relatively small and the gains or losses in terms of income will approach unity for most of the countries with a small tourism sector. Both these effects are illustrated in Figures C.8 and C.9.

6.3 Data and input parameters

The dataset required for this study needs to consist of bilateral trade and tourism expenditures along with transport costs and gross output data, and must therefore be assembled

¹⁰It should be noted that country j 's output elasticities $\gamma_j^h = Y_j^h / Y_j$ are determined endogenously. That is, in the new partial equilibrium, they actually take the value $\gamma_j^h = Y_j^{h'} / Y_j'$. Given that the expenditure shares are approximated for many countries for which input-output tables are not available (as described in Section 6.3), and—considering only small price changes—one can assume that $Y_j^h / Y_j \approx Y_j^{h'} / Y_j'$.

from a range of different data sources. Table 6.1 gives an overview. All values refer to year 2014 data. The variables describing transport supply are self-explanatory and need no further mention. The text below describes the collection and approximation of the demand variables.

Table 6.1: Overview of data and input parameters of the realised CGE model

Variable	Symbol	Unit	Trade	Tourism
Trade and tourism demand				
1 Price elasticity	ϵ^h	[-]	-5	-4
2 Transport cost share	f_a^h/p_a^h	[%]	OECD MTC	Sabre & WB
3 Output elasticity	γ^h	[%]	calculated	calculated
4 Expenditure share	α^h	[%]	calculated	calculated
5 Income (gross output)	Y^h	[2014 US\$]	OECD IOTs	WTTC
6 Expenditure	X^h	[2014 US\$]	calculated	WTTC
7 Bilateral expenditure	X_a^h	[2014 US\$]	UN Comtrade	calculated
Transport supply				
8 Fuel cost share	λ_{fuel}^h	[%]	0.5	0.3
9 Fuel price	$P_{\text{fuel(oil)}}^h$	[\$/bbl]	75	75
10 Carbon price	P_{CO_2}	[\$/tCO ₂]	variable	variable
11 Fuel related CO ₂ factor	η_f	[tCO ₂ /t _{fuel}]	3.114	3.156
12 Output related CO ₂ factor	η_y	[gCO ₂ /t.km]	6.5	N/A
		[gCO ₂ /p.km]	N/A	130
13 Round-trip factor	κ^h	[-]	1	2

Notes: 1) Trade: e.g. Anderson and Wincoop (2004), Simonovska and Waugh (2014), Head and Mayer (2014), Bas, Mayer and Thoenig (2015), Shapiro (2016). Tourism: Table 5.1 in Chapter 5. 2) OECD Maritime Transport Costs (Korinek, 2011), Sabre (2016), World Bank (2017). 5) OECD (2017a) Input-Output tables, World Travel and Tourism Council (2015). 7) UN Comtrade data via WITS (World Bank, 2016). 8) Sea: own estimate using a translog cost function and time charter rates and vessel specific data from Clarkson Research Services (2014), operating costs from Moore Stephens LLP (2015), and operating characteristics from IMO (2014) and IMO (2015). Results reveal a fuel cost share of 0.466 for bulk carriers, 0.568 for container ships, and 0.457 for tankers (containers have higher average sailing speed and thus a higher fuel burn relative to tankers and bulk carriers). Air: Johnston and Ozment (2013) found a value of 0.314 (this is one of the most recent studies using annual data from 1987 to 2009); Fischer and Kamerschen (2003) a value of 0.152, Caves, Christensen and Tretheway (1984) a value of 0.196, and Gillen, Oum and Tretheway, 1990 a value of 0.254. 11) Heavy fuel oil: IMO (2012). Jet fuel: Penner (1999). 12) Sea: Using 11) and average energy intensities from Gucwa and Schäfer (2013). Air: Table 3.1 and 6.1 in Schäfer et al., 2009. 13) See Equation 6.16.

Industry and total output. Trade data is taken from UN Comtrade via the World Integrated Trade Solution (WITS). Trade values refer to total industry trade and include agriculture, hunting, forestry, fishing, mining and quarrying (incl. crude petroleum), manufacturing (of all sectors), electricity, and gas. Not included are the sectors construction, wholesale and retail trade, and water works and supply.

Gross output and gross industry output values are obtained from the OECD Input-Output tables (IOTs). The latest available year is 2011. Gross output refers to all economic activity in all sectors (industry, tourism, and service sectors). Gross industry output refers to the industry sector.

Gross industry output is calculated for each of the 60 countries for which OECD IOTs are available, using the industry sectors which match the industry sectors of the UN Comtrade trade data. Gross output is calculated as gross industry output plus all other output¹¹.

¹¹The sectors in addition to the industry sectors that are considered in the calculation of gross output are:

Gross industry output and gross output data is then used—in combination with GDP, population, and labour data—to estimate gross output and gross industry output values for each of the countries for which OECD Input-Output tables are not available (see Appendix C.2 for a detailed description).

A country's domestic consumption in the industry sector (X_{jj}) is calculated by subtracting the total export value from gross industry output. A country's total consumption in the industry sector is obtained by adding to this value the total import value. A country's total expenditure in all sectors is obtained by subtracting net trade BOP values in goods and services from gross output. Net trade BOP data is obtained from the World Bank. Consumption and output data can then be used to calculate expenditure shares $\alpha^I = X^I/X$ and output elasticities $\gamma^I = Y^I/Y$ in the industry sector.

Transport cost shares are obtained from the OECD Maritime Transport Costs (MTC) database by dividing bilateral transport costs by CIF import values. The data is available over a 1991-2007 time period and for 43 importing countries (including EU15 countries as a custom union) from 218 countries of origin¹². Transport cost shares are calculated using data from the last available year and averaged across all product groups by country pairs. Missing data is estimated using the mean value of all bilateral transport cost measures by origin and destination country. The same approach and data is used to calculate bilateral value-to-weight ratios, which, in combination with trade data from WITS and the output related CO₂ factor in Table 6.1, is used to calculate the amount of CO₂ released and tax revenue generated using Equation 6.16. Trade-weighted sea distance data is taken from Newton (2009) and, in case of missing data, approximated using great-circle distance data from Mayer and Zignago (2011).

Tourism. Bilateral tourism expenditure is calculated by multiplying per person tourism expenditure in the destination country with the number of air passengers and iceberg travel costs by origin and destination country using $\bar{X}_{ji}^{\text{air}} \approx p_i^{\text{int'l}} \tau_{ji} N_{ji}$ (Equation 5.23). The number of air passengers by origin and destination country is obtained from air travel itinerary data of outbound flights from Sabre (see Appendix B). Iceberg travel costs are calculated using round-trip airfares by origin and destination country from Sabre and dividing it by person tourism expenditure in the destination country (see Chapter 5 and Equation 5.23 in particular). Per person tourism expenditure in the destination country is calculated from international tourism receipts and international inbound tourists data from the World Bank. Travel cost shares are then calculated by dividing the average round-trip airfare per person by the average spending per person in the destination country. The

construction, wholesale and retail trade, hotels and restaurants, transport, post and telecommunications, financial intermediation, real estate, renting, R&D and computer activities, education, health, and social work.

¹²The only statistical authorities who collect data on transport costs are the United States, Australia, New Zealand and Latin America (foremost Argentina and Brazil however). This information has been made available collectively in the MTC database. See Korinek (2011) for more information.

number of air passengers by country pair in combination with the output related CO₂ factor and round-trip factor in Table 6.1 are used to calculate the amount of CO₂ released and tax revenue generated using Equation 6.16. Great-circle distance data is taken from Mayer and Zignago (2011).

Gross tourism output Y^T is obtained by summing domestic and international tourism receipts data from the WTTC. Total tourism spending X^T is calculated by adding to the domestic tourism expenditures data from the WTTC¹³, the sum over all bilateral expenditures by origin country (see Section 5.3). Consumption and output data can then be used to calculate expenditure shares $\alpha^T = X^T/X$ and output elasticities $\gamma^T = Y^T/Y$ in the tourism sector.

Industry, tourism, and total output. All data is merged by reporting and partner countries. The final dataset consists of trade and tourism flows between 123 countries, of which 18 have a negligibly small tourism sector. Manual data adjustments were necessary for 17 countries where the sum of expenditure shares and output elasticities exceeded the value of one. In a last step, bilateral budget shares in each sector were calculated using Equation 6.8.

6.4 Policy scenario

At the time of writing, commitments towards reducing CO₂ from international transport have been made at the ICAO, but not at the IMO.

In 2010, the ICAO adopted sectoral aspirational goals, including an annual fuel efficiency improvement of 2% per year and carbon neutral growth from 2020 onwards (ICAO, 2016). The basket of measures available to achieve these goals include technological advances, operational improvements and the uptake of biofuels. In the short to medium term however the ICAO acknowledged that these measures are not enough to achieve a carbon neutral growth from 2020 onwards. The 39th ICAO Assembly therefore agreed on implementing a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) by 2020 (ICAO, 2016). In CORSIA, airlines have the option to offset emissions—in excess of the baseline target of a carbon neutral growth—by buying credits from the carbon market. Participation in the pilot phase from 2021-23 and first phase from 2024-26 is voluntary. During the second phase from 2027-35, all states with an individual share of aviation activities above 0.5% of the total, or whose cumulative share reaches 90% of the total, are required to participate. Least developed countries, SIDS, and landlocked developing countries (LLDCs) are exempted from participation, unless they volunteer to participate in the scheme. The amount of carbon emissions to be reduced each year will be deter-

¹³Domestic tourism receipts are equivalent to domestic tourism expenditures.

ined by exceeding 2020 carbon neutral growth levels of all countries participating in the scheme. The carbon price will be determined by the number of emission units offered and the number of emission units demanded. Emission units are issued by the UNFCCC Clean Development Mechanism (CDM) and the Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) programme. Because the supply of credits has far outstripped demand, the prices of Certified Emission Reductions (CER) credits of the CDM are currently as low as \$5 per tonne of CO₂ (Economist, 2012). How the price of CER credits might evolve in the future is difficult to predict. Considering a 5% p.a. growth rate in air transport, the amount of credits to be purchased each year by the aviation industry alone would amount to 20 million CER credits. With one billion of CER credits available however in 2012 (Economist, 2012), the increased demand for CER credits from the aviation industry is unlikely to cause significant price shifts. If more industries demand purchasing these credits in a post-Paris world however, prices may raise steadily and by a significant amount.

In contrast to the aviation industry, the shipping industry has to this date neither put long-term sectoral aspirational goals in place, nor agreed on a baseline year for peak CO₂ emissions (ICS, 2017). Shipping efficiency has been initially approached through the Energy Efficiency Design Index (EEDI) in 2011 as well as through mandatory Ship Energy Efficiency Management Plans (SEEMP). Given the progress made at the UNFCCC in 2015 in Paris and the progress made at the ICAO in 2016, the IMO is under pressure to agree on CO₂ reduction goals as soon as possible. IMO Member States will therefore begin the development of a road map to reduce CO₂ emissions in June 2017, with the intention to reach agreement of this roadmap by 2018 (ICS, 2017). Should the IMO decide to develop an MBM for international shipping, the International Chamber of Shipping (ICS) expressed that its preference would be for a global bunker fuel levy, while arguing that (i) a significant proportion of the tax revenue should be used for research into the development of alternative fuels for shipping and that (ii) any impacts on trade and sustainable development of developing nations should be addressed appropriately (ICS, 2017).

In line with the aspirations of the maritime transport industry, this study considers the policy case of introducing a global bunker fuel levy, in the form of a carbon price and charged per tonne of fuel purchased for consumption. From a modelling perspective, an exogenously determined carbon price yields into "similar" aggregate predictions as an endogenously determined carbon price with peak CO₂ emissions in a carbon offsetting scheme or an Emissions Trading Scheme (ETS). The results of this study are therefore also informative towards determining the demand impacts from CORSIA at different levels of carbon prices.

The considered policy scenario assumes a balanced transition path of the economy from an unconstrained to an environmentally-constrained international transport industry at different levels of carbon prices for each industry individually and jointly. Uptakes in tech-

nology and operational efficiency improvements are treated endogenously and modelled as a function of the carbon price as described next. To be able to investigate if global environmental policies in international transport trigger systematic patterns of discrimination against economically disadvantaged countries, no countries are exempt from the scheme.

The intuition towards modelling this policy scenario using the theoretical framework outlined above is as follows: After the legal framework of the policy scheme has been put into place at a point in time t , transport firms expect to be charged for the amount of emissions attributable to them at a point in time $t + 1$. Between the two periods $t - (t + 1)$, transport firms will employ a cost optimisation routine and consider to invest into fuel efficient technologies and adopt operational efficiency improvement measures to lower their costs. Along this balanced transition path, the uptake and gradual phase-in of these mitigation options will take place within the stated time period and reach full deployment at the point in time $t + 1$.

The extent of which technology uptakes and operational patterns materialise into cost reductions under different carbon prices are often illustrated by marginal abatement cost (MAC) curves. MAC curves indicate the abatement potential which could be achieved cost-effectively under different levels of carbon prices. The more mitigations employed, the higher the cumulative reductions in CO₂. As it is economically feasible to first implement the options with lower marginal cost, MAC curves are designed to show the available mitigation options by their declining cost-effectiveness. In theory, a continuous increase in the carbon price over time therefore ensures that the basket of available mitigation options is exhausted in sequence of declining cost-effectiveness of the mitigation options employed. Initially, the abatement potential therefore grows rapidly with higher carbon prices. Once the basket of mitigation measures at lower cost is exhausted however, any further, substantial reductions in CO₂ will be much more difficult to achieve.

This study links the level of technology uptake and operational improvement with levels of carbon prices using an approximated MAC curve for the aviation, and an approximated MAC curve for the maritime industry. Each MAC curve is described by a power function using the CO₂ abatement potential and the abatement cost as variables. Appendix C.2 shows the steps undertaken to fit each power function approximation to actual estimates of the MAC curve, after offsetting the curve to pass through the zero point. This approach imposes a strong simplification of the complex interactions between abatement potential and cost, and should therefore be regarded as a first order approximation under limited modelling capacity¹⁴. The approximation is however legitimate, as all other factors influ-

¹⁴The extent of which the mitigation options will be adopted not only depends on the carbon price, but also on the fuel price (see Equation 6.14), technology investment costs, discount rates, current fleet composition (old vs. new), fleet turnover rates, and the interactions of potential new technology with current technology (to name but a few). The quantification of technological uptakes and improvements in operational efficiency, their associated reduction in CO₂ and hence operational for cost reduction is therefore subject of rigorous integrated assessment models in aviation and maritime transport research

encing the uptake of these measures are assumed to remain unchanged between the initial and the new equilibrium in the model (see Definition 1).

The offset of the approximated MAC curves to pass through the zero point requires further clarification. MAC curves of the aviation and shipping fleet indicate substantial potential of emissions reduction at zero or negative marginal cost (Schäfer et al., 2015; Alvik et al., 2009). Given their cost-effectiveness, many of these mitigation options are already pursued by transport firms, despite any environmental taxes in place. Yet, the substantial amount of mitigation options at zero or negative cost still available illustrate that there may be significant barriers to implementation as a result of market failures such as liquidity shortages and information barriers. From an MBM perspective, this is problematic, as the appearance of these options suggests that a (carbon) price is not a sufficient driver to ensure a full uptake of these options. This is because of structural inefficiencies in the system which could arise from many sources including legacy effects, institutional structures, and contractual failures between ship and aircraft construction, ownership and operation. To account for these barriers in the model, the MAC curve is offset to pass through the zero point (see Appendix C.2). As such, the cost associated with these barriers is fully internalised and assumed to exactly counterbalance the negative differences in cost. This approach ensures that the mitigation options at zero or negative marginal cost are accounted for in the model. Their actual cost to implementation may however be different from this assumption and can only be quantified using sophisticated models, which are however beyond the scope of this study.

Denoting the percent reductions in CO₂ of the transport industry as $\phi^h = f(P_{\text{CO}_2})$, which take the form of a power function dependent on the carbon price as described in Appendix C.2, the cost reductions due to all of the technology and operational efficiency improvements employed by all firms in each sector are given by

$$\dot{\xi}_h \prod_{q_h=1}^{Q_h} (\hat{v}_q^h)^{\varepsilon_{\hat{v}}^{q_h}} \equiv (\chi')^{-\phi^h(\cdot)\lambda_{\text{fuel}}^h}. \quad (6.24)$$

At any given carbon price therefore, the mitigation options employed by a transport firm reduces its operational cost by the amount of CO₂ mitigated through the implementation of these options. It should be noted that at any given carbon price, not all of the mitigation options that are available will be adopted. Only the ones that are cost-effective will be considered by the transport firm at different levels of carbon prices.

From the overall cost increases the transport firm faces $(\chi')^{\lambda_{\text{fuel}}^h}$, the amount $\phi^h(\cdot)$ will be offset by the uptake of technology, whereas the amount $1 - \phi^h(\cdot)$ will be passed on the consumers in the form of price increases. To see this, Equation 6.24 can be used to

and therefore beyond the scope of this analysis.

substitute for the technology and operational cost part in Equation 6.20 to give

$$\widehat{C}_\tau^h = (\chi')^{\lambda_{\text{fuel}}^h} \dot{\xi}_h \prod_{q_h=1}^{Q_h} (\widehat{v}_q^h)^{\varepsilon_{\theta}^{q_h}} = (\chi')^{(1-\phi^h(\cdot))\lambda_{\text{fuel}}^h}.$$

In combination with Equation 6.16, the tax revenue is then calculated from the *remaining* amount of CO₂ released and the carbon price

$$R_{\text{CO}_2} = P_{\text{CO}_2} \sum_{h=1}^H \left(1 - \phi^h(\cdot)\right) \eta_y^h \kappa^h \sum_{i=1}^I \sum_{j=1}^I Q^h D_a^h, \quad a = \{ij, ji\}. \quad (6.25)$$

Equation 6.24 in combination with the power functions described in Appendix C.2 allow to obtain realistic values of changes in a firms' total costs without the need to specify dedicated models for technology uptakes and operational efficiency improvements. Any barriers to technology uptake, operational constraints, or volatility in carbon or oil prices (to name but a few) would violate the equilibrium condition described above and therefore result into higher (or lower) price increases as the ones calculated. The base case scenario underlying these calculations can therefore only reflect a balanced transition path of the transport industry over time.

Given that not all of the costs increases can be offset cost-effectively by the uptake of technology and operational mitigation strategies means that environmental policies in international transport eventually lead to demand implications in the form of price increases in each country.

How large can we expect the resulting price changes to be? Assuming that changes in wages remain insignificant ($\widehat{w}_i = 1$, for this section only) and that 50% of the cost increases can be offset by technology, Equation 6.21, in combination with Equations 6.15 and 6.24, simplifies to

$$\widehat{p}_a^h = 1 + \frac{f_a^h}{p_a^h} \left[\left(1 + \frac{\eta_f P_{\text{CO}_2}}{P_{\text{fuel(oil)}}}\right)^{0.5\lambda_{\text{fuel}}^h} - 1 \right], \quad a = \{ij, ji\} \quad (6.26)$$

A key variable to quantifying the changes in prices is therefore the share of transport costs in overall prices f_a^h/p_a^h , which takes an average value of 0.05 for manufacturing trade (Table A.2) and 0.83 for tourism (Table B.2). Given that transport costs only account for a small price share in international trade, the price increases in international trade will be much smaller than in international tourism.

Assuming a carbon price of \$25/tCO₂ and using the parameter values listed in Table 6.1, results (conditional on the wage adjustment) into a net price increase of 0.2% of goods imports and a 1.8% price increase of outbound tourism activities. Increasing the carbon price to \$150/tCO₂ results into price increases of 0.9% of goods imports and a 8.5% price increase of outbound tourism activities as illustrated in Figure 6.1.

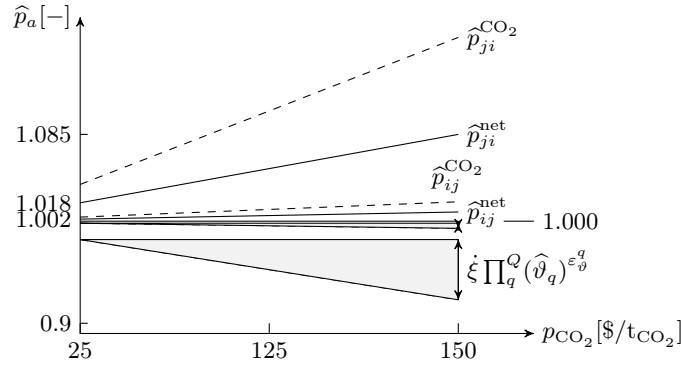


Figure 6.1: Illustration of net price increases in trade and tourism as a result of a carbon emissions pricing scheme in international transport, assuming a 50% cost reduction due to technology uptake and operational efficiency improvements.

Although the changes in wages are not yet taken into account at this stage, these results already demonstrate that consumers of outbound tourism services will be confronted with higher price increases as consumers of goods imports. Yet, how these cost increases will influence the aggregate consumer price index in each country will be determined by the expenditure share α^h and output elasticity γ^h . In comparison to trade, these shares are much smaller in tourism, thus leading to smaller welfare impacts.

On an aggregated consumers level therefore, given (i) the aggregated income and spending shares of trade and tourism in each country, (ii) the small share of international transport costs in prices on the demand side, and (iii) the small share of fuel costs in overall transport costs on the supply side, the price changes associated with environmental policies in international trade and tourism can be expected to generally remain small. Changes in a country's consumer price index in each sector, in combination with the income elasticity in Table 6.1, will then reveal the changes in real income in each country as per Equation 6.23.

6.5 Results

The welfare impacts associated with a carbon emission pricing schemes in international transport are dependent on the level of transport costs relative to consumer prices and a country's economic dependence on foreign spending and income. Figures 6.2, 6.3, 6.5, and 6.6 display¹⁵ price asymmetries in the industry and tourism sectors across countries (no data could be obtained for countries coloured in grey). The comparison of the two figures in each sector indicates the level and thus importance of transport costs in international trade and tourism. Figures 6.4 and 6.7 visualise the calculated changes in real income.

Starting with the industry sector, Figures 6.2 and 6.3 display asymmetries in supply prices

¹⁵Vector map data is obtained from Natural Earth.

and transport costs across countries.

The supply price in the industry sector refers to the price at the factory gate, exclusive of any transport costs (the FOB value), and is calculated by dividing the total export value ($Y_i^I - X_{jj}^I$) by the total export quantity ($Q_i^I - Q_{jj}^I$) in each country. The calculated prices at the factory gate are therefore indicative of the per-unit value of the exported goods. If data on a country's productivity level z_i were available, the asymmetries in supply prices could be used to show asymmetries in industry wages across countries. As CGE models merely calculate changes relative to a baseline however (the numeraire), the price levels need not be determined uniquely. As shown in Equation 6.23, only the differences in wages are calculated. The data displayed in Figure 6.2 is therefore not used in the CGE model to compute changes in real income. They are however useful to illustrate the relative importance of transport costs in international trade.

The data in Figure 6.2 indicates that supply prices are higher in countries with a focus on manufacturing exports (such as the US, Europe, China and India) and lower in resource producing countries (such as Russia, Australia, Canada, and Brazil). The absolute numbers in Figure 6.2, ranging from values close to zero to 17.4\$/kg, need to be interpreted with caution however as inaccuracies exist in the approximation of the total quantity exported (as these values are not observed in trade data), especially in countries with a relatively low industry output, exacerbating the statistical error, as is the case for countries in Africa for example.

Figure 6.3 illustrates the role of transport costs in international trade by *origin* country. The data in this figure is calculated by dividing total transport costs $\sum_{i \neq j}^I q_{ij}^I f_{ij}^I$ by the total export value $Y_j^I - X_{jj}^I$ (CIF) and is therefore indicative for the level of transport costs a country faces to export their goods to foreign countries. The total export value is also given by $\sum_{i \neq j}^I q_{ij}^I p_{ij}^I = \sum_{i \neq j}^I q_{ij}^I w_i^I \tau_{ij}^I / z_i^I$. The average share of total transport costs in the total export value can therefore also be expressed as $\sum_{i \neq j}^I f_{ij}^I q_{ij}^I / \sum_{i \neq j}^I (w_i^I / z_i^I + f_{ij}^I) q_{ij}^I$. Relative to total export values, the data in Figure 6.3 illustrates that transport costs are highest (with values above 20%) for resource exporting countries, such as Australia, Russia, Brazil and Canada, as a result of the relatively lower per-unit values (low p_{ij}) of the exported goods. Remoteness, leading to higher transport costs (high f_{ij}), however, also plays a role. Figure 6.3 also indicates that a common pattern of high versus low transport costs across developed versus developing countries cannot be identified.

Figure 6.4 illustrates changes in real income \widehat{W}_j (using Equation 6.23) across countries, after a carbon price of \$300/tCO₂ on goods trade by sea has been introduced. These results represent general equilibrium results which are obtained from the realised CGE model. Figure 6.4 is different from Figure 6.3 as it also includes a country's economic dependency on the industry sector—in terms of spending α_j^I as well as income γ_j^I —and

the equilibrium changes in wages. Figure 6.4 therefore gives the only coherent view on the welfare impacts associated with carbon emissions pricing schemes in international trade.

Since the carbon revenue is not used as a rebated lump-sum to consumers, all countries face a reduction in real income, after a carbon emissions pricing scheme in the international maritime industry has been introduced. All values shown in Figure 6.4 are therefore negative. Figure 6.4 illustrates that it is not developing countries who will perceive the highest welfare losses. Rather, the opposite is the case: Russia, Canada, Australia and Saudi Arabia are among Ecuador, Peru, Bolivia, Chile, Paraguay, South Africa, Vietnam and Egypt with the highest welfare losses of around 0.1%. Countries with high entrepôt trade, such as Belgium, the Netherlands, Singapore, and Hong Kong also experience a higher welfare loss¹⁶. The extent of which policies are discriminating against developing countries or countries with a low GDP per capita will be evaluated in detail further below. The relative differences in welfare impacts across countries displayed in Figure 6.4 will remain approximately identical under higher carbon prices, as a result of the underlying modelling assumptions. The model also assumes that the introduction of or a change in the carbon price does not have any influence on the transport network and trade routes. This can be seen from Equation 6.21, where the only bilateral variable relating to transport costs to calculate changes in the consumer prices is in fact the share of transport costs in consumer prices f_{ij}^I/p_{ij}^I . To account for competitive pricing with variable markups in the transport industry, one would need to make the increase in transport costs \hat{C}_τ^I to be dependent on trade routes. Given that transport costs are however only a small fraction of consumer prices (Figure 6.4) and that a country only buys a small amount from foreign countries¹⁷, incorporating such price dynamics on selective trade routes would result into only marginally different results.

Continuing with the tourism sector, Figures 6.2 and 6.5 display asymmetries in supply prices and transport costs across countries in the tourism sector.

The supply price in the tourism sector refers to the price paid by foreign visitors in the destination country, exclusive of any travel costs, and is calculated by dividing the total of international tourism receipts $Y_j^T - X_{jj}^T$ by the total number of international tourist arrivals in each country $N_j^T - N_{jj}^T$. The calculated prices in the destination country are therefore indicative of the amount spent on tourism activities (including the prices paid for accommodation) per visitor for all tourism activities in each country on average. If data on the number of activities consumed in each country over a given time period were available, the asymmetries in supply prices could be transformed to show asymmetries in tourism wages across countries.

¹⁶Import values are manually adjusted to account for re-exports.

¹⁷Changes in real income are calculated on a country level. This is accomplished by aggregation over all trade routes, including the ones, which may not subject to any variable markups.

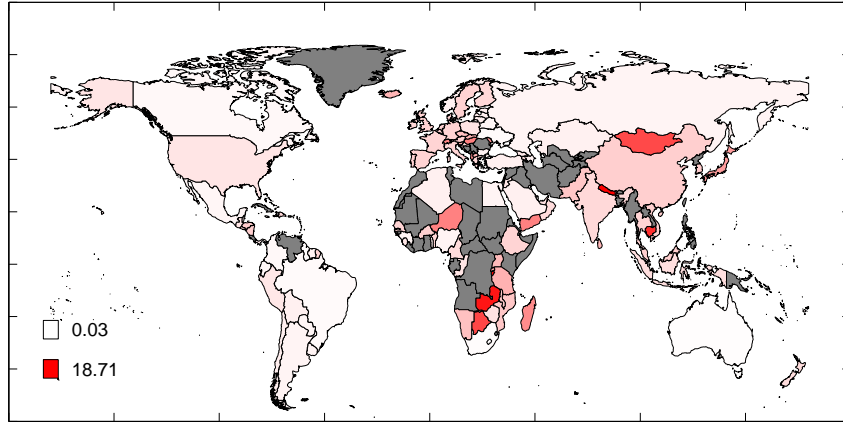


Figure 6.2: Average supply price $w_i z_i$ [\$ /kg] (Trade)

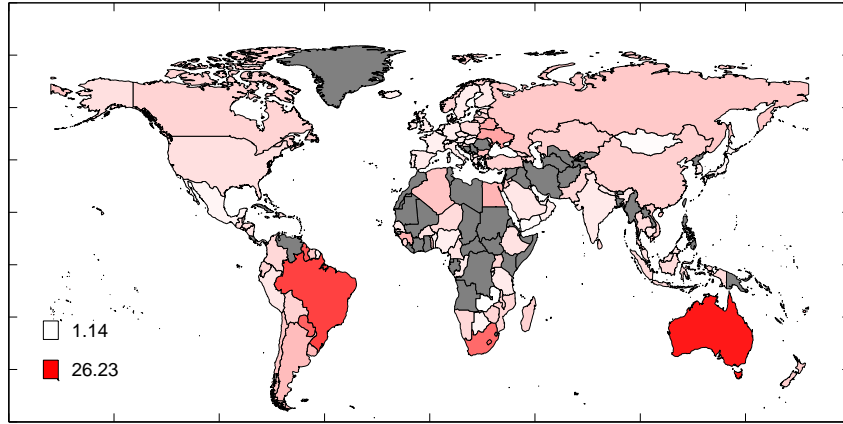


Figure 6.3: Average transport costs relative to consumer prices f_{ij}/p_{ij} [%] (Trade)

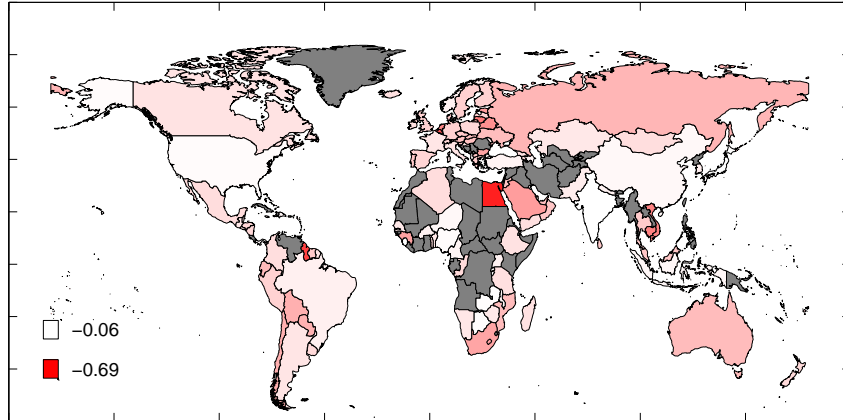


Figure 6.4: Change in real income \widehat{W}_j [%] due to a carbon price of \$300/tCO₂ in international sea transport (Trade)

The data in Figure 6.5 indicates that the prices paid by international inbound visitors are higher in developed countries (US, UK, Sweden, Switzerland, Australia) and lower in developing countries (such as Mexico, China, Algeria, Egypt). Among others, one reason for this are the relatively lower wages in developing countries. Another reason is that the tourism sector is relatively less developed in some of these countries, thus offering

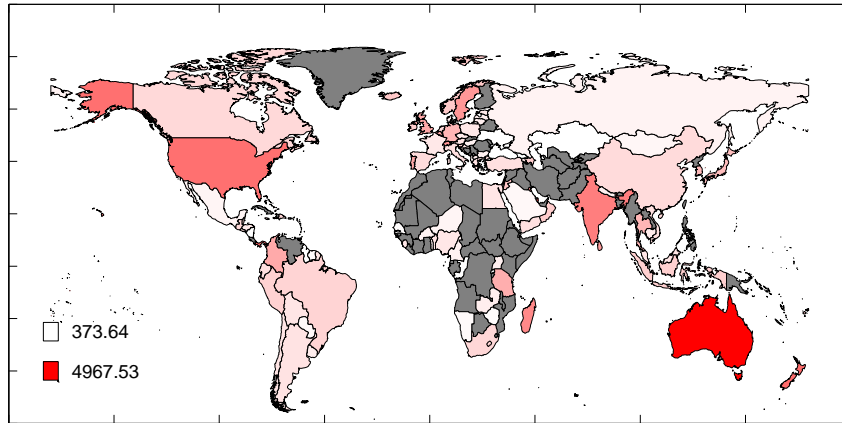


Figure 6.5: Average supply price w_i [\$/int'l inbound tourist] (Tourism)

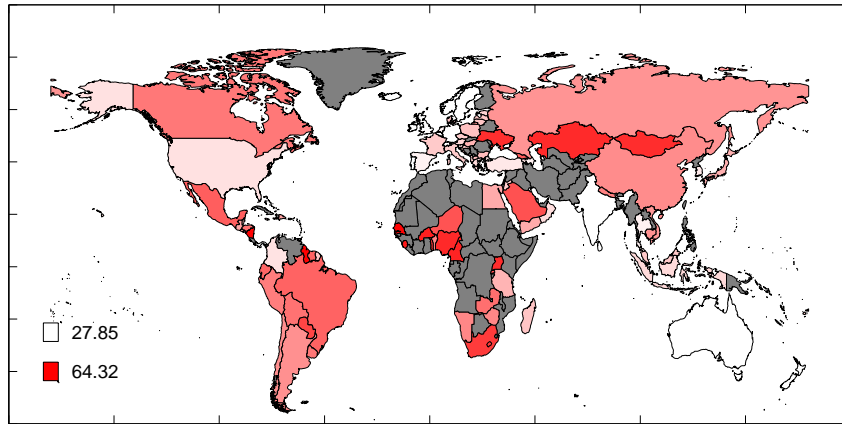


Figure 6.6: Average travel costs relative to consumer prices f_{ji}/p_{ji} [%] (Tourism)

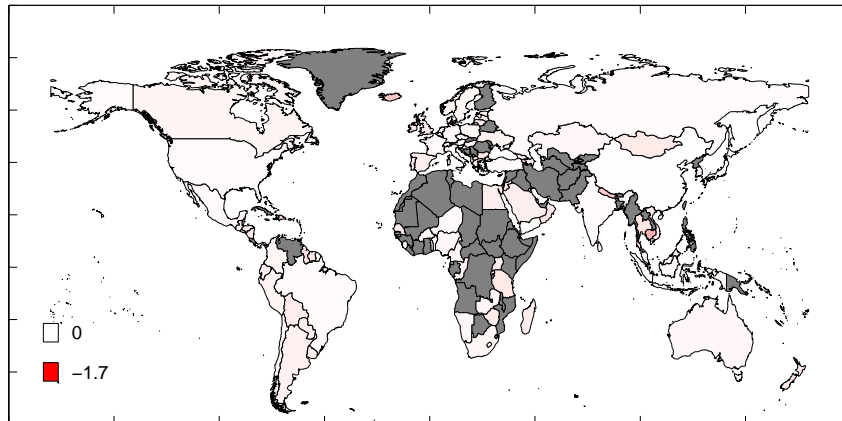


Figure 6.7: Change in real income \widehat{W}_j [%] due to a carbon price of \$300/tCO₂ in international air transport (Tourism)

less tourism services for visitors to consume. The average prices paid by tourists in each country range from as low as \$325 per person to as high as \$5,000 per person. As in the case above for average supply prices in the industry sector, statistical reporting issues however exist. Australia for example is among the countries where average tourism spending per person is highest. International tourism receipts include payments to national carriers

for international transport. Hence, flights from London to Sydney using the flag carrier airline of Australia (Qantas) are included in this statistic, whereas flights from London to Sydney using e.g. the flag carrier airline of the UK (British Airways) are not. Hence, as some of the airfares paid by tourists are taken into account proportionally, the reported international tourism receipts are higher for countries with a flag carrier airline, as is the case for Australia for example. The statistical error of the amount of travel costs included in prices (or in total international tourism receipts respectively) is exacerbated for remote countries (resulting into higher travel costs) in combination with relatively lower supply prices (or spending per person), as is the case for India for example.

The data depicted in Figure 6.5 is used to calculate bilateral tourism flows X_{ji} as these are not observed in the data. They therefore also play a role in determining the value of transport costs relative to consumer prices between country pairs given by $f_{ji}^T/p_{ji}^T = f_{ji}^T N_{ji}^T / \left[\left(p_i^{\text{int'l}} + f_{ji}^T \right) N_{ji}^T \right] = f_{ji}^T / \left(p_i^{\text{int'l}} + f_{ji}^T \right)$, where $p_i^{\text{int'l}} \approx w_i^T$.

Figure 6.6 illustrates the role of transport costs in international tourism by *destination* country. The data in this figure is calculated by dividing total international travel costs $\sum_{i=1}^I f_{ji}^T N_{ji}^T$ by total international tourism receipts $Y_j^T - X_{jj}^T$ (inclusive of travel costs). These numbers are therefore indicative for the level of transport costs a country faces to receive international inbound tourists from all over the world. International tourism receipts are also given by $\sum_{i=1}^I N_{ji}^T p_{ji}^T = \sum_{i=1}^I N_{ji}^T w_i^T \tau_{ji}^T$. The average share of total travel costs in total international tourism receipts can therefore also be expressed as $\sum_{i=1}^I f_{ji}^T N_{ji}^T / \sum_{i=1}^I \left(w_i^T + f_{ji}^T \right) N_{ji}^T$. Relative to total international tourism receipts, the data illustrates that the travel costs are higher (with values up to 64%) for countries where supply prices are lowest, as is the case in most of Africa and Latin America, as well as Saudi Arabia, Ukraine, and Mongolia, next to China and most of South East Asia. Given that travel costs take up a significant share of the overall prices paid by international inbound tourists as indicated in Figure 6.6, remoteness, leading to higher travel costs, plays a more significant role in tourism than in trade. Figure 6.6 also indicates that a common pattern of high versus low travel costs across developed versus developing countries cannot be identified.

Figure 6.7 illustrates the change in real income \widehat{W} (using Equation 6.23) across countries, after a carbon price of \$300/tCO₂ on passenger travel by air has been introduced. These results represent general equilibrium results and also include a country's economic dependency on the tourism sector—in terms of spending α_j^T as well as income γ_j^T —and the equilibrium changes in wages. Figure 6.7 therefore gives the only coherent view of the welfare impacts associated with carbon emissions pricing schemes in international tourism.

As is the case for international trade, the carbon revenue in international tourism is not used as a rebated lump-sum to consumers, and all countries therefore face a reduction in real income after a carbon emissions pricing scheme in the international aviation industry

has been introduced. All values shown in Figure 6.7 are therefore negative. The countries with the highest welfare impacts are the Maldives, Fiji, Cyprus, Jamaica, Cambodia, St. Lucia, Malta, and Mauritius (given their small size, they are hardly visible in the plot). These results indicate that most of the small island developing states (SIDS) will be among the countries with the highest welfare impacts due to two main reasons. First, given their remoteness, travel costs are high and therefore take up a significant share of the overall costs faced by international inbound tourists to visit these countries (high f_{ji}/p_{ji}). Small changes in travel costs therefore lead to relatively higher reductions in demand. Second, tourism represents a major source of income for SIDS (high γ_j^T) and changes in real income in the tourism sector are therefore felt by the entire economy. On an absolute level, the welfare losses can therefore also be higher in the tourism than in the industry sector as a result of relatively high travel costs in combination with a relatively high economic dependence on foreign tourism income. While many countries also have a high economic dependence on foreign spending and income in the industry sector, the transport costs in international trade remain generally low, which thus leads to smaller welfare impacts. Finally, examining the larger group of all developing countries against a common pattern of higher welfare impacts leads to the conclusion that such a pattern cannot be identified from Figure 6.7. The extent of which developing countries and SIDS are subject to systematically higher welfare losses will be analysed in detail further below.

Before turning to the general results, total transport output and CO₂ emissions of the realised and actual transport system are compared against each other. Table 6.2 gives an overview. Within the limits of the realised model, consisting of trade and tourism between 123 countries, the numbers compare well to the values in the literature and can therefore be used as benchmark for calculating the tax revenue.

Table 6.2: Validation of the realised international maritime and air transport system in 2014

Variable	Unit	Int'l maritime industry		Int'l aviation industry	
		model	literature	model	literature
Transport work RTK	billion t.km	88,403	97,363	N/A	N/A
Transport work RPK	billion p.km	N/A	N/A	3,366	3,838
Emissions	million tCO ₂	575	607	438	454

Notes: Literature values obtained from UNCTAD (2014), ICAO (2014), and IEA (2015). Table 1.1 contains detailed emission values by transport sector.

The realised CGE model is used to investigate changes in real income in each country at carbon prices ranging between \$25/tCO₂-\$300/tCO₂. The employed optimisation algorithm builds on the work of Head and Mayer (2014) and solves for the vector of equilibrium wages given by Equation 6.22 using a dampening factor. The algorithm has been extended to additionally account for *dynamic* price changes as a result of changes in wages given by Equation 6.21. To ensure model convergence, the dampening factor for the dynamic changes in prices is set at a slightly lower value than the dampening factor for the changes in wages. The magnitude of the dynamic prices changes remain generally small (as illustrated in Figures C.2 and C.3) but are of quantitative importance given that a carbon

price in international transport also only induces small changes in prices. In addition, the algorithm has been extended to solve for equilibrium changes in wages in international tourism. This can be accomplished by interchanging the origin and destination indices before starting the optimisation run, provided that the data structure adheres to the notation used in this chapter (using the indices ij for trade and ji for tourism).

Table 6.3 contain the results of changes in real income in the industry and tourism sector after a carbon emissions pricing scheme has been imposed on the international transport industries. Column 2 in each table reports the *average* price increase across countries of consumer goods and services, which are purchased from foreign countries¹⁸. Column 3 reports the *average* changes across countries in domestic expenditures in the industry and tourism sectors. Average changes in real income (abbrev. RI) per capita in column 4 and changes in Gross World Product (GWP) in column 5 are calculated using $\sum_{j=1}^I Y_j (\widehat{W}_j - 1) / \sum_{j=1}^I L_j$ and $\sum_{j=1}^I \text{GDP}_j (\widehat{W}_j - 1)$ respectively, where the total number of workers L and GDP data in each country is taken from the World Bank. The tax revenue in column 6 and total CO₂ abatement potential in column 7 are calculated using Equations 6.25 and 6.24. Finally, the economic cost in column 8 is calculated by dividing the change in GWP by the total change in CO₂ abatement.

Depending on the carbon price ranging from \$25/tCO₂ to \$300/tCO₂, the price increases of goods imports range from 0.3% to 1.2% (column 2). As a result of these price increases, the goods produced domestically become *relatively* cheaper. Consumers (as well as firms) therefore purchase a larger quantity of goods produced domestically. The results in Table 6.3 indicate that this increase in domestic consumption amounts to 0.5% to 2.1% (column 3). As domestically produced goods are more expensive than imported goods, this shift causes an increase in the consumer price index and hence a reduction in demand. The price increases are therefore felt by consumers (through an increase in the price index) as well as by firms in the industry sector (through a reduction in demand). Table 6.3 shows that per capita real income is reduced by \$15 to \$58 on average (column 4). GWP¹⁹ reduces by \$24 billion to \$93 billion (column 5). Although the supply induced price changes remain relatively small, the impacts in terms of real income and GDP are large. This is because international trade broadly affects all consumers in a country as a result of a large consumption share and a relatively large income from the industry sector. The total tax revenue raised by the carbon emissions pricing scheme in international maritime transport reaches \$13 billion to \$78 billion per year (column 6), while 52 Mt to 316 Mt of transport related CO₂ are abated cost-effectively each year (column 7; assuming zero growth in maritime transport output over time). In the maritime transport industry, the maximum

¹⁸It should be noted that these numbers do neither represent changes in the consumer price index nor "net" increases in transport prices. The relative price changes in column 2 in the Table 6.3 refer to price changes of imported goods or price changes of tourism services. The goods price is inclusive of transport costs. The price paid for tourism services includes the costs paid for (air) travel.

¹⁹Approximated by adding up the GDP of all of the 123 countries in the dataset.

Table 6.3: International trade and tourism in a CO₂-constrained world

(1) Carbon price \$/tCO ₂	(2) Av. \hat{p}_{ij}^I %	(3) Av. $\hat{\lambda}_{jj}^I$ %	(4) Av. delta RI \$/cap.	(5) Delta GWP \$bn	(6) Tax rev. \$bn	(7) Delta CO₂ MtCO ₂	(8) Economic cost \$GWP/tCO ₂
International trade in a CO ₂ -constrained world							
25	.3	.5	-15	-24	13	-52	464
50	.5	.9	-26	-42	24	-96	438
75	.7	1.3	-35	-55	33	-133	415
100	.9	1.5	-41	-65	41	-166	394
125	1	1.7	-46	-73	48	-194	375
150	1	1.8	-49	-78	53	-219	358
175	1.1	1.9	-52	-83	58	-241	343
200	1.1	2	-53	-86	63	-260	329
225	1.2	2	-55	-88	67	-278	316
250	1.2	2.1	-56	-89	70	-294	304
275	1.2	2.1	-56	-90	73	-308	293
300	1.2	2.1	-58	-93	78	-316	293
International tourism in a CO ₂ -constrained world							
25	1.7	2.6	-5	-7	10	-26	291
50	3.1	4.7	-9	-13	20	-46	288
75	4.3	6.4	-12	-18	28	-63	285
100	5.3	7.9	-14	-22	36	-77	282
125	6.1	9.1	-16	-25	44	-89	280
150	6.9	10.2	-18	-28	51	-100	277
175	7.5	11.2	-19	-30	58	-109	275
200	8.1	12	-21	-32	64	-117	273
225	8.6	12.7	-22	-34	70	-125	271
250	9.1	13.4	-23	-35	76	-132	269
275	9.5	14	-24	-37	82	-138	267
300	9.9	14.5	-25	-38	88	-144	265
International trade and tourism in a CO ₂ -constrained world							
25	-	-	-20	-31	23	-77	407
50	-	-	-35	-55	44	-142	389
75	-	-	-46	-73	61	-196	373
100	-	-	-55	-87	77	-242	359
125	-	-	-62	-98	91	-283	345
150	-	-	-67	-106	104	-318	333
175	-	-	-71	-113	116	-350	322
200	-	-	-74	-118	127	-378	311
225	-	-	-77	-122	137	-403	302
250	-	-	-79	-125	147	-426	293
275	-	-	-80	-127	156	-446	285
300	-	-	-83	-131	166	-460	284

Notes: The base year for calculations is 2014 using data and input parameters as specified in Table 6.1.

potential of mitigation options is exhausted at a carbon price of approximately \$300/tCO₂ (Alvik et al., 2009; IMO, 2011a). Table 6.3 therefore stops at a carbon price of \$300/tCO₂. Finally, column 8 of Table 6.3 indicates that it costs between \$293 and \$490 in GWP to reduce one tonne of CO₂ in the maritime transport industry (column 8). This cost is decreasing with higher carbon prices. That is, the higher the carbon price, the less the economic cost to reduce a further tonne of CO₂ in the international maritime transport

industry.

The relative price increases in the tourism sector are larger than the price increases in the industry sector. This is because the transport related costs (air travel costs) represent a much larger share of the prices paid of international inbound visitors for tourism activities (including hotel expenses etc.) in the destination country²⁰ (Table B.2). Depending on the carbon price ranging from \$25/tCO₂ to \$300/tCO₂, the results indicate that the lump-sum price increases in tourism range from 1.7% to 9.9%. The relative changes to the tourism sector are therefore substantial, even at relatively low carbon prices. Domestic tourism expenditure increases range from 2.6% to (as large as) 14.5%. On the other hand, reductions in per capita real income are smaller in tourism than in trade, and range from \$5 to (only) \$25 on average. This is because the tourism sector only represents a small share of overall spending and income in each country (given by small values of α_j^T and γ_j^T). Connected to this are smaller reductions in GWP, ranging from \$7 billion to \$38 billion per year. Given the high energy intensity of air travel, the total tax revenue raised by the carbon emissions pricing scheme in international air transport reaches \$10 billion to \$88 billion per year, while 26 Mt to 144 Mt of transport related CO₂ are abated cost-effectively each year (assuming zero growth in air transport output over time). The tax revenue and abatement potential in the international air transport industry are therefore comparable in levels to the tax revenue and abatement potential in the international maritime transport industry. Similarities in these numbers are a direct result of the combination of differences in scale and energy efficiency. While sea transport is a large scale industry, the release of CO₂ per unit of transport output (in tonne-km) is low (Table 6.1). In comparison to maritime transport, (international) air transport is still a relatively small industry (Table 6.2), but with much a higher release of CO₂ per unit of transport output (in passenger-km). Finally, column 8 of Table 6.3 indicates that it costs between \$265 and \$291 in GWP to reduce one tonne of CO₂ in the international air transport industry. As in the case above, this cost is decreasing with higher carbon prices. That is, the higher the carbon price, the less the economic cost to reduce a further tonne of CO₂ in the international air transport industry.

The lower part of Table 6.3 combines the trade and tourism results so as to show the demand implications along with the CO₂ abatement potential if the carbon emissions pricing scheme is jointly applied to both the international maritime and air transport industry. In this case, per capita real income reduces by \$20 to \$83 and GWP reduces by \$31 billion to \$131 billion per year, while the tax revenue reaches \$23 billion to \$166 billion with a CO₂ abatement potential of 77 Mt to 460 Mt per year. Putting these numbers into context reveals an economic cost of \$284 to \$407 in GWP per tonne of CO₂.

The results in Table 6.3 are dependent on the price elasticities of demand in each sector.

²⁰It should be noted that these numbers do not represent relative changes in airfares. Rather, they are reflective of how much the overall expenditure for tourism, inclusive of travel costs, increases.

The results of running the CGE model with higher and lower elasticities than the ones specified in Table 6.3 are shown in Tables C.1 and C.2 in Appendix C.3. The price increases in both sectors due to a carbon tax in international transport are unaffected by the value of the demand elasticity (column 2 of Tables C.1 and C.2). A higher demand elasticity however results into smaller welfare impacts as demand is relatively more elastic. In this case, a higher amount of foreign spending is substituted with domestic spending (see Equation 6.6). The opposite is true for lower values of the demand elasticities where a smaller amount of foreign spending is substituted with domestic spending. The value of the demand elasticity therefore results into significant changes in domestic spending X_{jj}^h as indicated by the changes in relative domestic expenditures $\hat{\lambda}_{jj}^h$ in each sector (column 3 in Tables C.1 and C.2). Because real income is affected by both changes in income and changes in foreign spending (Equation 6.23), the changes real income remain largely unaffected by the changes in the demand elasticities. Slightly higher impacts due to lower demand elasticities as well as slightly lower smaller impacts due to higher demand elasticities become however visible at higher carbon prices. The calculation of the delta in GWP takes the changes in real income as input and therefore mirrors these observations. The tax revenue and CO₂ abatement potential are solely related to the components of transport supply and remain therefore unaffected by changes in the demand elasticities. As a result of only marginal changes in GWP and no changes in CO₂ abatement, the economic cost in terms of GWP to reduce one tonne of CO₂ in international transport is robust with respect to changes in the demand elasticities as indicated by the results in column 8 of Tables 6.3, C.1, and C.2.

Another key finding not yet described in detail is the declining trend of the economic cost in GWP per tonne of CO₂ with higher carbon prices which is apparent in all sectors, even at higher or lower demand elasticities. In other words, the economic cost to reduce one additional tonne of CO₂ in international transport becomes smaller at higher carbon prices. This declining trend is a result of the differences between the rate of GWP and the rate of CO₂ abatement (noting that both of them are non-linear trends however). The abatement potential of both transport industries is higher at higher carbon prices as indicated by the MAC curves in Figure C.1 and in Alvik et al. (2009) and IMO (2011a). The results in Tables 6.3, C.1, and C.2 indicate that the CO₂ abatement in both industries occurs faster than changes in prices materialise into changes in GWP, which thus explains the declining trend in economic cost. Once the maximum CO₂ abatement potential is reached however, the delta in CO₂ would remain constant while the GWP would continue to decline. After the maximum CO₂ abatement potential has been reached therefore, the economic cost to reduce one additional tonne of CO₂ would start to increase again (not shown in the results).

What carbon price should be adopted? A higher carbon price leads to higher reductions in CO₂ and a higher tax revenue on the one hand, but also to higher reductions in real income

and GWP on the other. The economic cost per unit reduction in CO₂ is decreasing with higher carbon prices. At high carbon prices however, both industries could potentially reach their maximum abatement potential. This limit may shift further upwards if R&D spending in both industries increases as a result of the introduction of carbon emission pricing schemes.

The carbon price of \$150/tCO₂ deserves particular mention. The results in Table 6.3 illustrate that at a carbon price of approximately \$150/tCO₂ applied to both the aviation and the maritime transport industry would yield a tax revenue of approximately \$100 billion per year. The international transport industries could therefore—within reasonable limits (as illustrated by Figure 7.1)—become the primary source of global climate finance, through mobilising 100\$ billion per year, representing the agreed collective quantified goal to assist developing country Parties under the Paris agreement with respect to mitigating and adapting to climate change (UNFCCC, 2015; see Section 2.4). The carbon price of approximately \$150/tCO₂ therefore indicates a benchmark for policy design if both international transport industries are mandated to become the primary source of finance for the global climate fund.

As the policy scenario investigated does not account for any rebate mechanism, the results obtained from the CGE model can also be used to investigate if carbon emissions pricing schemes in international transport would lead to any form of discrimination, most notably, against developing economies. Using the changes in real income (in percent) as dependent variable and three binary variables, one accounting for developing economies, one for SIDS, and one for LLDCs, the probability of a systematic pattern of discrimination against these three country groups can be evaluated in a logistic regression. Table 6.4 contains the results.

A systematic pattern of discrimination against developing countries for the international maritime, the international aviation, and the combined policy scheme cannot be identified. The null hypothesis of a systematic pattern of discrimination against developing countries is rejected at the 1% in all of these cases. If these schemes were discriminating, the coefficient estimate of the corresponding binary variable would need to take a negative value, thus indicating a systematic pattern of higher reductions in real income $\widehat{W} < 1$ for these countries. Table 6.4 however shows that this is not the case. The empirical results also support the results in Figures 6.2 and 6.3, where a common pattern of high versus low transport costs across developed versus developing countries cannot be identified. Many developing countries specialise in the manufacturing of goods that can be produced competitively using lower wages. These goods have a relatively higher unit value than e.g. goods in resources trade, and the share of transport costs in overall prices is therefore lower. This in turn leads to relatively lower price increases and explains why developing countries are less prone to large price shifts and hence welfare impacts. In international tourism, the welfare impacts can either be relatively larger or smaller, given that tourism

represents a major source of income for some of the developing countries (high γ_j^T), but not for others (low γ_j^T). These differences do not lead to a pattern of *systematic* discrimination, as illustrated by the results in Table 6.4.

Table 6.4: Tests for discrimination against economically disadvantaged countries

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Variable	Dependent variable					
	\widehat{W}_j^I	\widehat{W}_j^T	\widehat{W}_j	\widehat{W}_j^I	\widehat{W}_j^T	\widehat{W}_j
<i>Developing country</i> [binary]	0.09 (3.5)	0.51 (12.8)	0.26 (10.1)	0.10 (4.2)	0.11 (4.3)	0.10 (5.9)
<i>SIDS</i> [binary]	0.27 (4.9)	-1.40 (-24.3)	-0.62 (-13.4)	0.27 (4.4)	-0.66 (-21.1)	-0.15 (-5.5)
<i>LLDCs</i> [binary]	0.43 (14.2)	-0.02 (-0.3)	0.26 (7.9)	0.42 (15.1)	-0.26 (-8.2)	0.15 (6.7)
GDP per capita [\$ /cap]	-	-	-	1.0e-06 (2.8)	2.2e-06 (4.2)	1.7e-06 (5.8)
Carbon price [\$ /tCO ₂]	-	-	-	-1.6e-03 (-34.1)	-1.5e-03 (-26.8)	-1.6e-03 (-43.5)
Expenditure share α_j^I [-]	-	-	-	-1.55 (-21.4)	-1.19 (-18.4)	-1.36 (-29.6)
Income elasticity γ_j^I [-]	-	-	-	1.47 (19.4)	1.09 (16.2)	1.21 (23.3)
Expenditure share α_j^T [-]	-	-	-	-9.15 (-9)	-24.12 (-42.4)	-12.07 (-25.7)
Income elasticity γ_j^T [-]	-	-	-	3.85 (6.7)	-1.32 (-7.5)	-1.51 (-9.2)
χ^2 test $H_0 : \beta_{\text{Devl.}} \leq 0$	0.0002	0	0	0	0	0
χ^2 test $H_0 : \beta_{\text{SIDS}} \leq 0$	0	1	1	0	1	1
χ^2 test $H_0 : \beta_{\text{LLDCs}} \leq 0$	0	0.6344	0	0	1	0

Notes: Each column represents a separate logistic regression using GLM (Papke and Wooldridge, 1996) and 3,444 computed observations at different levels of carbon prices. Z-statistics are reported in parentheses. "Developing country", "SIDS", and "LLDCs" are binary variables, which take the value of one if the country is a developing country or a SIDS, and zero otherwise.

The null hypothesis of a systematic pattern of discrimination against SIDS is rejected at the 1% level for the international maritime policy scheme. The opposite case is however true for the international aviation, and the combined policy scheme, where the null hypothesis is failed to be rejected at the 1% level. SIDS will therefore, on average, experience a higher loss in real income than all other countries participating in the international aviation or combined policy scheme, a pattern, which can be explained by the following two reasons. First, SIDS are remote islands and the travel costs paid by tourists to get there are therefore high. As a result, the overall prices paid by international inbound tourists in these countries includes a high proportion of transport costs. A change in transport costs will therefore lead to relatively higher impacts on prices and hence demand. Second, the economy of SIDS is largely dependent on the tourism sector, which thus results into a high value of the income elasticity γ_j^T . In combination with a relatively low domestic spending in the sector (low α_j^I), the reductions in wages $\widehat{w}_j^T < 1$ (as a result of less international inbound tourists), lead to large reductions in real income \widehat{W}_j (see Equation 6.23).

The case for LLDC's is less clear. The null hypothesis of a systematic pattern of discrimination against LLDCs is rejected at the 1% level for the international maritime and

combined policy scheme, but is failed to be rejected at the 1% level for the international aviation policy scheme. The discrepancies in the results in column 3 and 6 are a result of the underlying data limitations. For one third of the LLDCs analysed, no data on domestic and outbound tourism expenditure could be obtained. The expenditure share for these countries is therefore zero. Once these countries are excluded from the regression, the null hypothesis of a systematic pattern of discrimination against LLDCs is failed to be rejected at the 1% level for the international aviation policy scheme in column 3 as well (not shown). The results in column 6 control for these data limitations by holding the expenditure shares and income elasticities fixed, and are therefore the preferred estimates. The systematic pattern of discrimination against LLDCs can be explained as follows. LLDCs are geographically remote countries (given that they are land-locked), and therefore also face (similar to SIDS) higher transport costs. The calculated data supports this claim: average travel costs relative to consumer prices f_{ji}/p_{ji} are systematically higher than for all other countries in the dataset. Faye et al. (2004) argue in similar ways. Like SIDS therefore, LLDCs will be exposed to higher welfare impacts due to relatively larger price changes in tourism. In the combined policy scheme, no systematic pattern of discrimination against LLDCs can be identified. This is because the industry sector is much larger than the tourism sector in almost all of the LLDCs. The welfare changes due to tourism therefore become insignificant relative to the welfare changes due to trade.

All other results in Table 6.4 are robust against the inclusion of additional explanatory variables, such as GDP per capita, the carbon price as well as expenditure shares and income elasticities. The coefficient estimates of GDP per capita and carbon price are small in absolute value as a result of their relatively large scale if measured in \$/capita and \$/tCO₂. The coefficient estimates of the expenditure shares and income elasticities have the expected sign. A country spending more on international trade and tourism will be subject to price increases of a larger share of goods and activities and therefore experience a higher welfare loss. Vice versa, countries with large domestic industry and tourism sectors can compensate the welfare loss with a higher spending on domestic goods and services. In the tourism sector however (column 6), the income elasticity obtains a negative value as a result of the large asymmetries in terms of spending (α_j^T) and income (γ_j^T) in many countries.

6.6 Summary

Carbon emissions pricing schemes in international transport trigger changes in consumer prices worldwide, the extent of which is dependent on the level of transport costs relative to consumer prices, and the shares of a country's foreign spending and income in the industry and tourism sectors. To quantify these price changes and the resulting implications in terms of demand, this chapter developed a computational general equilibrium model of the world

economy, consisting of the industry, tourism, and international transport sectors. Demand is modelled using the gravity equations for international trade and tourism; transport supply is modelled using a cost function of a representative transport firm, with a reduced-form power function of endogenous technology uptake and operational improvements. Both models are linked using equilibrium prices.

In equilibrium supply equals demand. Introducing a price shock to consumer prices in trade and tourism as a result of a carbon tax in international transport introduces economic imbalances in income and spending in each country. Using counterfactual exercises, the changes in prices, spending, and income between the initial (without a carbon tax) and the new equilibrium (with a carbon tax on international transport) can be made dependent on only variable, the vector of wages in each country. A CGE model of the trade, tourism and international transport sectors is then obtained by employing an optimization algorithm to solve for the changes in wages in each sector and country. The CGE model is based on 2014 economic data from a range of different data sources, including input output tables and transport costs data from the OECD, trade data from the UN Comtrade database, trade BOP data, international tourism receipts and international inbound tourists data from the World Bank, as well as domestic tourism receipts data from the WTTC. Demand elasticities are taken from the literature (trade) and Chapter 5 (tourism).

In international trade, the data indicates that transport costs *relative to* the goods prices are highest for resource exporting economies and lower for manufacturing exporting economies, as a result of large differences in the unit value of the exported goods. Remoteness, leading to higher transport costs, plays a subordinate role.

In international tourism, the data indicates that transport costs *relative to* the prices paid by international inbound tourists in the destination country are highest for countries where the cost of labour is low, and lowest for countries where the cost of labour is high, as a result of large differences in wages. Remoteness plays a more significant role than in international trade. SIDS and LLDCs are geographically remote countries, and average travel costs relative to consumer prices are systematically higher than for all other countries in the dataset.

The policy scenario considered uses a global bunker fuel levy as an economic tool to reduce the emissions from the international maritime and air transport industries. As an exogenously determined carbon price yields into "similar" aggregate predictions as an endogenously determined carbon price with peak CO₂ emissions in the model, the computed results are also informative towards determining the demand impacts associated with offsetting schemes or Emissions Trading Schemes (ETS) in international transport. The CGE model, data and policy scenario is used to analyse changes in real income in each country, using a balanced transition path of the world economy from an unconstrained to an environmentally-constrained international transport industry at different levels of carbon

prices for each international transport sector individually and jointly.

In the range of carbon prices between \$25/tCO₂-\$300/tCO₂, consumer prices increase only marginally in goods trade (0.3-1.2%), whereas in tourism (given that transport costs take up a significant share of the overall prices paid by international outbound tourists) the lump-sum price increases in activities can be significant (2-10%). The welfare impacts as a result of these price changes consist of impacts on the demand as well as on the supply side. On the demand side, the consumer price index increases, thus leading to a reduction in real income. On the supply side, the impacts are determined by the differences in spending and income in each sector. The demand elasticities in international trade and tourism take a value of four to five. Given this relatively elastic demand on the one hand, and increases in prices in each sector on the other, domestic relative to foreign spending increases by 0.5-2% in the industry sector and by 3-15% in the tourism sector. These increases lead to a higher gross output and thus income in each sector. They however also lead to higher prices in each sector, given that these goods and services are then produced and consumed domestically. Whether or not these changes lead to welfare losses or gains is determined by the differences in consumption and output. If output is higher than consumption in a sector, consumers benefit from higher income. If output is smaller than consumption in a sector, consumers loose from higher prices.

As the industry sector is a major source of income, and therefore much larger than the tourism sector in many countries, the welfare impacts in terms of real income are much larger in the industry than in the tourism sector, despite the fact that the average price increases in tourism are larger than in trade. Average annual per capita real income reduces by \$15-\$60 if the international maritime industry is subject to a global carbon tax. It reduces (only) by \$5-\$25 if the international aviation industry is subject to a global carbon tax. Similar observations can be made for the reductions in gross world product, dropping by \$25-\$90 billion in trade and by \$10-\$40 billion in tourism, on a 'once only' basis and subject to the level of the carbon price. Given the higher energy intensity of air versus sea transport, the tax revenues raised by the schemes in each sector are similar, reaching \$15-\$80 billion in the international maritime and \$10-\$90 billion in the international aviation industry annually, while 50-300 Mt and 25-150 Mt of transport related CO₂ are abated cost-effectively in each sector each year.

Dividing the amount of CO₂ abated by the quantitative impacts in terms of GWP reveals an economic cost of \$300-\$450 to reduce on tonne of CO₂ in the international maritime industry and an economic cost of \$250-\$300 to reduce on tonne of CO₂ in the international aviation industry. This cost reduces with higher carbon prices as the CO₂ abatement in both industries occurs faster than changes in prices materialise into changes in GWP. At higher carbon prices, it therefore costs less to reduce one further tonne of CO₂ in international transport.

A carbon price of \$150/tCO₂ applied to both the aviation and the maritime transport industry would yield a tax revenue of \$100 billion per year. This amount corresponds to the latest agreed collective quantified goal of raising money for global climate finance.

Furthermore, the model results indicate that a carbon emissions pricing scheme in international transport would in general not lead to any systematic pattern of discrimination against developing countries. Carbon emission pricing schemes in the international air transport industry however would lead to a pattern of systematic of discrimination against SIDS as well as LLDCs, indicating the need to exempting these countries from participation.

Chapter 7

Discussion and future work

7.1 Discussion

Limitations of the study. This study is limited by the model restrictions imposed by economic theory, and its model simplifications and data limitations.

Starting with the model restrictions imposed by economic theory, and as mentioned in Chapter 3, gravity equations of international trade (and tourism) are considered as one of the most empirically robust and theoretically sound findings in all of economics (Head and Mayer, 2014, Costinot and Rodríguez-Clare, 2014). They however also impose strong restrictions on the data. First, all variables need to enter in multiplicative form. Second, the estimated coefficients are representative for all flows by country pair in the cross-section. The log-linear form of the gravity equation restricts transport costs to be specified as an *ad valorem* to the prices in the partner country (excluding travel costs). As shown in Tables 4.1 and 5.2, the level of transport costs is also dependent on price levels. Assuming transport costs proportional to prices is therefore not entirely accurate but imposed by the multiplicative form of the gravity equation. This functional form also imposes the restriction to specify the price elasticity of demand to be *common* to all country pairs. Demand might however be more elastic for some country pairs, and be less elastic for others. The elasticity estimates obtained from gravity equations are a representative average of all these different elasticities by country pair. The predictions of the model can therefore also only take average elasticities into account, and may be accurate for the majority of country pairs in the dataset, but less accurate for relatively smaller flows (given the log transformation of the variables). The predictions (in absolute levels) for smaller countries (having smaller flows) need therefore be interpreted with respect to these limitations.

Model simplifications include the omission of fixed transport costs, the reduced-form description of technology uptake, and the omission of the relocation of production emissions.

Starting with the omission of fixed transport costs, a number of steps would be required to implement a heterogeneous firm model instead of a homogeneous firm model in this study. In international trade, fixed costs have been found to be quantitatively important (Bernard, Jensen and Lawrence, 1995; Bernard and Jensen, 1999) and the gravity equation should therefore take the form of the Melitz (2003) model with fixed exporting costs. In international tourism however, the role of fixed costs on bilateral tourism spending needs to be examined once data becomes available. As a result, fixed costs may, or may not be quantitatively important in tourism, leading to either a heterogeneous or a homogeneous firm model. It should be noted that, as the model is specified sector by sector, the combination of a heterogeneous firm model in trade with a homogeneous firm model in tourism would in principle be possible. Second, to be able to predict changes in consumers' prices as a result of changes in fixed costs, data on fixed costs by country pair in trade (and tourism) needs to be collected. Third, the cost function on the supply side would need to take the form of a total cost function instead of a variable cost function. The total cost function would consist of variable and fixed costs. The variable cost function would need to take into account the costs, which are treated as fixed in the short-run, whereas the fixed costs part would need to take into account the costs which are treated as fixed in the long-run. Fourth, the change in fixed costs of an (average) transport firm as a result of a change in the carbon costs needs to be examined. Given that the carbon costs can be linked directly to the amount of fuel consumed via an emissions factor, they can be classified as "pure" marginal costs. A carbon tax however triggers large investments into technology and operational efficiency improvements that cause a change in fixed costs through changes in capital costs. Fifth, the amount of fixed costs of a transport firm to be passed on to the consumers in the form of price increases needs to be investigated. These five steps illustrate the complexity and large data requirements involved. Once accomplished, a trade (and tourism) model with fixed costs would allow to additionally quantify the dynamic welfare impacts on trade (and tourism) as a result of carbon emissions pricing schemes in international transport. Such a model could reveal that the welfare impacts are larger than the ones quantified in this study. This is because the dynamic welfare gains tend to be larger in a model with fixed exporting costs (Sampson, 2016).

The simplifications related to modelling technology uptake and the reductions in emissions are described in Section 6.4 and Appendix C.2. A precise forecasting of technological uptakes and efficiency improvements is however not required, provided that the resulting cost reductions homogeneously apply to the entire transport fleet and therefore approximately uniformly to all country pairs. To remain competitive however, a transport firm may choose to e.g. only equip the largest vehicles with fuel efficient technology that serve the trade and tourism routes with the highest demand. Such individual operational strategies would yield into different prices on competitive trade and tourism routes. As the welfare impacts by country are calculated from all trade and tourism routes by country pair however, relatively large changes in prices on particular trade or tourism routes lead to only

relatively small changes (if any) in the aggregated welfare impacts by country.

The same reasoning can be applied to justifying the assumption of constant markups. Some trade and tourism routes may be subject to variable markups under carbon emission pricing schemes. It is unlikely however that all trade and tourism routes are subject to variable markups given the large number of existing shippers, ship charterers, and airlines, characterising a competitive market. A model accounting for variable markups would therefore very likely result into similar aggregated predictions on a country level.

Trade also generates an environmental impact through relocating emissions of production i.e. the transfer of activities or production facilities to other market economies, with different production technologies and hence different production emissions. Grubb et al. (2015) show that the embedded carbon in goods imports can account for a significant share of a country's total CO₂ emissions. A similar principle applies to tourism activities, where some countries have a higher energy efficiency and sustainable tourism standards than others. A shift in demand therefore also triggers changes in the release of CO₂ emissions related to tourism by country. Both these changes in emissions on the trade and tourism side are not taken into account in this study.

Limitations of the study also exist with respect to the data. These include statistical reporting errors of bilateral spending in international trade, the approximation of bilateral spending in international tourism, and the approximation of gross output (overall and by sectors) and transport costs by origin and destination country in case of missing data. The detailed results of this study (obtained for each country individually) need therefore be interpreted with respect to these data constraints. On an aggregate level however (incl. the changes with respect to per capita average income and gross world output), the statistical error remains within reasonable limits.

How realistic are the computed results? At carbon prices of 50, 150, and \$300/tCO₂ in international air and maritime transport, gross world product reduces by \$55, \$106, and \$131 billion (see Table 6.3). According to World Bank estimates, countries in the range of these values in terms of their national GDP are Bulgaria, Ecuador, and Ukraine. If all the demand impacts were borne by only one country, the implications would be large. If these impacts are spread across all countries however, the implications are relatively small, resulting into a per capita reduction in real income of \$35, \$67, and \$83 respectively.

For another comparison, according to World Bank estimates, gross world product amounted to \$78,658 billion in 2014. The above mentioned policy cases therefore correspond to a 0.07%, 0.13%, and 0.17% reduction in gross world product. With annual growth rates of gross world product of above 3% on average, the introduction of carbon emission pricing schemes in the international air and maritime transport industry would therefore not trigger a global economic crisis, even if a carbon price of \$300/tCO₂ would be introduced

over a relatively short period of time. It should be noted that the reductions in GDP and real income only occur once, in moving from the initial to the environmentally constrained scenario. Once this transition has been accomplished, the world economy is a new equilibrium state and no further demand impacts are to be expected if the carbon price remains unchanged.

For a third comparison, the increases in fuel costs due to a carbon price can be compared against historically high and low fuel prices. Figure 7.1 shows historic jet fuel and Brent oil spot prices (FOB) from the EIA (2017), which have been normalised to February 2017 prices. The drop in prices during the 2007-08 global financial crisis and the enforced production of oil from OPEC countries starting in 2015 are clearly visible in the data. From February 2017 onwards (indicated by a vertical line), the graph then shows the increase in the fuel price index associated with the introduction of a carbon price (assuming a \$25/tCO₂ increase per year). This increase resembles values of the one plus the CO₂ tax equivalent of net fuel prices, given by $\chi = 1 + \frac{\eta_f P_{CO_2}}{P_{fuel(oil)}} \geq 1$ in Equation 6.15. The intersection of fuel prices with the second vertical line indicates the expected fuel price increase, equivalent to a carbon price of \$150/tCO₂. Although a carbon price of \$150/tCO₂ may be associated with an aggressive policy, the historical data in Figure 7.1 illustrates that the international transport industries both have seen hypothetical carbon prices of (at least) \$150/tCO₂ in the past.

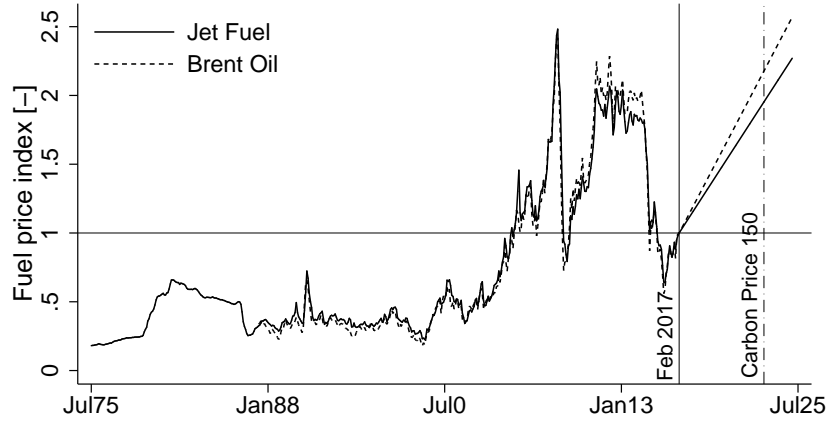


Figure 7.1: Historic versus future, carbon price related, changes in fuel price indexes. Historic data from EIA (2017). Future price changes calculated by assuming a gradual increase in carbon prices.

For a fourth and final comparison, the counterfactual results obtained in this study can be compared with results in the literature. Most commonly found in the literature are values relating to the gains from trade. That is, the counterfactual exercises are calculated using the hypothetical case of moving the economy to an autarky equilibrium. Mathematically, this can be accomplished by assuming that foreign trade shocks become infinitely large $\tau = +\infty$. In autarky, a country needs to produce all goods by itself, using labour, which

is probably more expensive, and technology, which is probably less efficient (in the most simplistic case). This leads to higher goods prices, and thus a decrease in real income (leaving aside the changes in income on the supply side as a result of an increase in production as per Equation 6.23). The gains from trade can then be calculated using $G = 1 - \widehat{W}$. Costinot and Rodríguez-Clare (2014) show that the welfare gains from trade reach an average of 4.4% in most of the OECD countries, using the simple Armington model as the theoretical baseline. As the price shocks investigated in this study using a CGE model are smaller than the infinitely large price shocks in the autarky case, the gains from trade associated with a reduction in transport costs in this study must be smaller than the overall gains from trade (which are associated with the autarky case). Figure C.6 shows that gains from trade associated with the reduction in transport costs by amounts of $1/\chi$ using a carbon price of \$300/tCO₂ can be as high as 1% for some countries, but with a global average of 0.25% for most of the countries in the dataset. These results compare well to the overall gains from trade, given the relatively smaller magnitude of exogenous prices shocks investigated in this study.

Similar comparisons of the CGE model results can be made with the counterfactual results in Chapters 4 and 5. The gains from tourism reach on average 1.6% (Table B.3). The welfare impacts associated with slow steaming are on average -0.34%, not accounting for sector-by-sector expenditure shares however in terms of α_j (the welfare impacts are therefore larger). As slow steaming represents one of the key mitigation options under carbon emission pricing schemes in international maritime transport (at least for containerised trade and hence manufacturing imports), the price increases in terms of carbon costs and time costs should ideally be jointly taken into account. In doing so, the predicted welfare impacts in the industry sector in each country would become slightly larger.

Comprehensively taken into account, these four comparisons illustrate that the computed results and assumptions on the demand as well as the supply side are within realistic limits.

The link of carbon emission pricing schemes in international transport with tax revenue and welfare. The calculated tax revenues in Table 6.3 compare well to the estimates in the study by the World Bank, the IMF, and the OECD (World Bank, 2011), but generally obtain a relatively smaller value. The smaller values of this study are a result of additionally taking technology uptakes into account. Without technology uptake, the tax revenue would be higher as international transport emissions would be higher (subject to the level of the carbon price).

It should be noted that, if the carbon tax from Equation 6.16 is "recycled within the model" and thus assumed to take the form a rebated lump-sum to consumers as in e.g. Shapiro (2016), a country's real income will also be affected by the revenue the carbon price generates from all imports or tourist departures respectively, given by $Y_j = \sum_{h=1}^H \left(Y_j^h + P_{CO_2} \eta_y^h \sum_{i=1}^I Q^h D_a^h \right)$, $a = \{ij, ji\}$. Subject to each country's import and

outbound tourism intensity, the revenues from the carbon emissions pricing schemes can potentially outweigh any welfare losses. If this is the case for several countries, such a policy scheme could eventually create imbalances in terms of welfare such that some countries will benefit, while others will lose. Shapiro (2016) showed—by imposing a policy design with lump-sum rebated environmental taxes in trade—that low-income countries are generally disadvantaged as a result of relatively smaller total import values. From an economic modelling point of view, the rebated lump-sum to consumer represents an interesting case worthwhile to investigate. From the current political point of view however, a lump-sum rebated environmental tax is not realistic, as it has neither been taken into consideration at the ICAO nor at the IMO over the past several years in international negotiations. To close the realised model of this study also in terms of the generated tax revenue, the model would need to be embedded within a dynamic integrated model of climate change and the economy, such as the DICE model described in Nordhaus (1994).

In this study, the predicted welfare changes across countries but relative to each other remain identical at higher (or lower) carbon prices. This is because the cost increases to a transport firm are treated homogeneously across all trade and tourism routes. Any patterns of discrimination therefore also remain identical at higher (or lower) carbon prices. In Chapter 5 the pattern of discrimination against SIDS is already apparent by rank-ordering countries by the size of the gains from international tourism (Table B.3). These results are obtained without the use of a CGE model. The ICAO also decided to exclude SIDS, as well as LLDCs, from the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), though, the reason for excluding them has not been mentioned explicitly. In international trade, it is widely believed that international maritime policies will lead to a discrimination against developing countries (IMO, 2011b, ICS, 2017). This study however shows, that this is not the case. Ultimately, what matters is the amount of transport costs embedded in overall consumer prices (either in terms of purchases of goods or tourism services and activities). The non-discriminating arguments can also be made by only analysing the data as demonstrated in Figures 6.2, 6.3, 6.5, and 6.6 - without any theoretical frameworks and complex modelling algorithms imposed on the data.

Exempting countries from carbon emission pricing schemes in international transport may prohibit systematic patterns of discrimination in some cases (as e.g. shown for the international aviation policy case), but also trigger a potential for carbon leakage, especially if the exempting rules apply to many of the larger countries participating in the scheme. For example, original equipment manufacturers (OEMs) could strategically buy from countries which are exempt to lower their costs. A rise in net CO₂ would then occur, if the supplier country the OEM is buying from is less energy efficient than the country the OEM used to buy from. In this case, carbon leakage would occur, if these strategic buying decisions by the OEM are made with the intention to avoid carbon costs. The extent of which carbon leakage may occur in exempting SIDS and LLDCs from international aviation policies is

however limited for two reasons. First, the tourism sector of SIDS and LLDCs is small in comparison to the tourism sector in large countries like the US. SIDS and LLDC's would therefore not be able to accommodate large shifts in tourism demand, which are triggered by tourists from many countries with the goal to avoid carbon leakage. Second, the choices of where to leak to are limited if only a few countries are exempt from the scheme. Grubb (2014) notes that most of the studies undertaken suggest that the scale of potential carbon leakage (due to national environmental policies) is small, certainly far less than the scale of expected emissions savings, and actually also not the main concern of many governments. Rather, many politicians are concerned they lose their competitive advantage in the industry or tourism sectors (or one particular sub-sector of it). Competitiveness is key to ensuring economic growth and long-term investments. These concerns led quite often to a special treatment of internationally competitive industries in environmental regulations around the world (Grubb, 2014). Exempting certain industries from the participation in emissions pricing schemes in international transport would be impracticable. International transport policies may undeniably influence the competitiveness of some countries, for the better or the worse. At the same time however, one could argue that many countries are exposed to such market dynamics through the volatility in oil prices in any case. Changes in oil and thus fuel prices also trigger changes in consumer prices. These changes are exogenous too and take the form as carbon tax levied directly on the carbon content of the fuel. Figure 7.1 demonstrates that these fluctuations can be substantial and be of comparable size of carbon emission pricing schemes with a carbon price in the range of \$25/tCO₂-\$150/tCO₂.

7.2 Future work

To account for endogenous adjustment mechanisms of the aviation and maritime transport industries, the model in Chapter 6 could be extended by linking the trade model and tourism model with partial equilibrium models of the air and marine transport system. This integrated assessment model (IAM) would allow to study policy cases of the international aviation and maritime industry in which e.g. variable markups, mode shifts from air to sea transport, and the uptake of technology in each industry are taken into consideration. The added value of such a modelling approach to the results presented in this thesis is however most likely to be limited for two reasons. First, a more rigorous modelling approach on the supply side does not overcome the modelling simplifications and data restrictions on the demand side as described above. Statistical inaccuracies on the demand side may therefore prevent the model to precisely capture small changes on the supply side. Second, changes in real income are computed on a country level, thereby taking domestic and bilateral expenditure shares into account (given by λ_{jj} , λ_{ij} , and λ_{ji}). Given that domestic expenditure shares are much larger than bilateral expenditure shares, even relatively larger

are nested within the blue loop of trade and tourism demand. The grey arrows indicate the exchange of information to conduct welfare calculations. These calculations can be carried out independent of the iterative calculations in the blue loop, unless a boundary condition is established that links welfare impacts with changes in the carbon price as indicated by the line c.

The demand models are sector-specific but not sector and mode-specific. In international trade, the gravity equation is specified for total goods trade which includes both, air and ocean freight transport. To account for endogenous mode shifts due to changes in transport costs however (e.g. from air to ocean freight), the model needs to disaggregate sector-specific demand to sector and mode-specific demand, perform the relevant calculations at this level, and then aggregate sector and mode-specific transport costs to sector-specific transport costs. The model system in Figure 7.2 therefore also bears a resemblance of the aggregate-disaggregate-aggregate (ADA) model in Ben-Akiva and De Jong (2013), where disaggregation is performed over firms to includes logistic decisions at the firm level that feed into a network assignment model.

The demand model is based on expenditures, income, and budgets shares in each country. Given wages, the output of the demand models are bilateral trade and tourism demand in units of US dollars (top right box in Figure 7.2). To link trade and tourism demand to transport supply, a unit conversion needs to be performed. The value-to-unit model transfers bilateral trade and tourism demand in US dollars into bilateral transport demand in tonne-km and passenger-km (arrows 1 and 2 in Figure 7.2). As in OECD ITF (2015), this model could represent a Poisson regression model that takes into account attributes of product, time, distance, and any trade barriers (common language, contiguity, etc.). Input to the transport choice model are origin-destination (OD) flows and transport costs. The choice model then predicts how OD transport demand changes, relative to baseline OD flows. Consistent projections of oil and carbon prices under a set of GHG stabilisation scenarios serve, together with projections of trade and tourism demand, as inputs to the models of the global transport system. Given demand, technology, and exogenous input prices (carbon price, oil price, etc.), these models then calculate changes in transport costs. As the choice model and the supply model depend on both, transport costs and transport demand, the level of equilibrium transport costs needs to be determined iteratively (indicated by the loop of 4, 5, 7, and 8). As the trade and tourism model are specified in terms of aggregate demand (i.e. the demand over all transport modes in each sector), mode-specific transport costs in each sector need to be aggregated to sector-specific transport costs. The demand model takes transport costs, and trade and tourism flows (in the form as budget shares) as inputs and calculates the changes in wages in each sector (the general equilibrium trade and tourism impact, GETI). The vector of changes in wages then predicts changes in bilateral trade and tourism flows, over which the model iterates until the changes in wages are below a predefined threshold level and a new equilibrium

state is found. The welfare model can then transfer the equilibrium changes in the price index and income in each country, and the total of CO₂ emissions reduced globally, into a quantitative welfare measure. Conditional on the selected GHG stabilisation scenario underlying the calculations, the IAM predicts the welfare impacts in each country, the tax revenue, the energy consumed, the emissions emitted, and the technology utilized.

The carbon price can be treated as either exogenous or endogenous. The carbon price would become endogenous if the annual release of CO₂ emissions or welfare is treated as fixed, as indicated by the lines a and b. The former case would represent a scenario of carbon-neutral growth of the international transport industry, if a sustained growth can be maintained in retrospect to increases in costs and their impact on demand. Furthermore, the IAM could also be used to study the policy case of a combined regime, where the aviation and maritime transport industry would be treated conjointly under the same policy measure.

Chapter 8

Conclusions

The introduction of carbon emissions pricing schemes in the international aviation and maritime industry will lead to an increase in the costs associated with the international transport of goods and the international travel of tourists. Conditional on the amount of CO₂ a transport firm is capable to reduce cost-effectively through the uptake of technology and operational improvements under a given a carbon price, these costs increases will be passed down the supply chain to consumers in the form of price increases.

Affected by these price increases are the prices of goods imported from foreign countries as well as the lump-sum prices paid for accommodation and travel services for tourism activities in foreign countries. This is because in both cases, the overall prices paid by consumers include the cost of transport. The magnitude of these price changes therefore simply depends on the level of transport costs, relative to the level of these prices itself. In resources trade, transport costs take a significantly higher share, relative to the goods price due to relatively lower per-unit values (measured in \$ per tonne) of the traded goods. In manufacturing trade, the per-unit values are higher, and the level of transport costs relative to the goods price is therefore lower. Resources trade will thus be subject to higher price increases than manufacturing trade under a carbon emissions pricing scheme in international maritime transport. In tourism, countries with relatively low labour costs (most of Africa and Latin America) will be affected more by price increases in international air transport than countries with relatively high labour costs (e.g. the US, Australia, Western Europe). If the costs associated with travelling to foreign countries are high relative to the amount spent on accommodation and other services in the destination country, any price increases in the international air transport will lead to significant increases in travel budgets and therefore higher impacts in terms of tourism demand.

The extent of which these price changes materialise into changes of the consumer price index in each country and sector depends on the ratio of domestic to foreign expenditure. In the industry sector, this is the ratio of goods produced and consumed in the home

country relative to the consumption of imported goods. In the tourism sector, this is the ratio of domestic tourism expenditure relative to international (outbound) tourism expenditure.

The extent of which the changes in the price index in each sector materialise into changes in a country's overall consumer price index depends on the output elasticity and expenditure share in each sector. Trade is interlinked with the industry sector, representing the most important and thus biggest sector in most of the countries. The output elasticity and expenditure share in the industry sector are therefore high (approx. 0.43). In tourism, the output elasticity and expenditure share are small (approx. 0.035), as the tourism sector represents a relatively small sector for most of the countries which are industry-intensive. Changes in the sectoral price index due to price changes in trade therefore materialise into significantly higher changes in the overall consumer price index than changes in the sectoral price index due to price changes in tourism.

At the same time, any changes in the consumer price index will cause a shift in demand. The sensitivity of demand to price changes is measured by the price elasticity of demand in each sector. The micro-theoretical foundation of trade and tourism demand take the form of a gravity equation, which are empirically robust and theoretically sound. In this context, the demand elasticities represent macro-level predictors of bilateral trade and tourism flows. In the industry sector, the trade elasticity therefore measures the proportionate change in the expenditure of imported goods relative to the expenditure of goods produced at home. In the tourism sector, the (outbound) tourism (demand) elasticity measures the proportionate change in the expenditure on tourism activities consumed elsewhere (including any travel costs) relative to expenditure on tourism activities consumed at home. The large literature on estimates of the trade elasticity suggests a value of five. Results in this thesis suggest a value of the tourism elasticity of four.

Lastly, changes in demand cause a change in income in each sector. A change in income can have an overall positive or negative impact on welfare. If the expenditure share is larger than the income share (output elasticity) in a country, any increases in income (as a result of a reduction in foreign expenditure) will lead to a welfare loss, as consumers are affected more by higher prices than they can benefit from higher income. If the expenditure share is smaller than the income share in a country, any increases in income will lead to a welfare gain, as consumers are affected more by higher income as they are by higher prices. As the expenditure share is approximately equivalent to the income share in most of the countries (even by accounting for foreign income and spending), the impacts on welfare through changes in income are relatively small in comparison to the welfare impacts through changes in consumer prices.

In general equilibrium, total expenditure equals total income in each country. Equilibrium changes in real income can therefore be determined in a CGE model consisting of the

industry, tourism, and international transport sectors. In such a model, international transport takes the form of extended supply.

If the carbon price takes the form of a global bunker fuel levy, the percent increase in fuel costs amounts to the level of the carbon price, relative to the price of the petroleum-based fuel. Faced with these costs increases, transport firms will invest into more fuel-efficient and cost-effective technologies and operational measures to mitigate these extra costs. Marginal abatement cost curves of the international air and maritime transport industry indicate a substantial potential of emissions reductions at low marginal costs. Once these abatement options are exhausted, the abatement costs increase rapidly, while leading to smaller reductions in CO₂. As the basket of mitigation measures available is not sufficient to reduce the emissions to zero, even under extremely high carbon prices, a transport firm will inevitably face an increase in fuel costs if faced with a carbon price. The extent to which changes in fuel costs lead to changes in the firms total operating costs is determined by the fuel cost share and the level of aggregate, cost-effective emission reductions available. Under the assumption of constant markups, the resulting cost increases net of technology paybacks to a transport firm are then passed on to consumers in the form of price increases.

In summary, the changes in the consumer price index in each country depend on four cost shares, the value of the demand elasticity, and the level of endogenous technology uptake. The four cost shares are (i) the level of the carbon price relative to the price of petroleum-based fuels, (ii) the share of fuel costs in a transport firm's total operating costs, (iii) the share of transport costs in consumer prices, and (iv) the level of domestic to foreign expenditure. As all these shares are relatively small, the changes in the consumer price index and income in each country can be expected to remain relatively small.

Subject to the limitations imposed by the model and data, the resulting economic cost of reducing one tonne of CO₂ in both the air and maritime transport industries corresponds to approximately \$400 in global value added (GWP). This cost reduces with higher carbon prices as the CO₂ abatement in both industries occurs faster than changes in prices materialise into changes in GWP.

In international trade, at a carbon price of \$150/tCO₂, consumer prices increase by 1.0%, domestic consumption increases by 1.8%, per capita real annual income decreases by \$49 on average, and gross world product drops by \$78 billion and on a 'once only' basis, while \$53 billion of tax revenue is raised and 219 Mt of transported related CO₂ is abated cost-effectively each year. At this carbon price, the economic cost of reducing one tonne of CO₂ in the international maritime industry corresponds to \$360 in global value added.

In international tourism, at a carbon price of \$150/tCO₂, consumer prices increase by 6.9%, domestic consumption increases by 10.2%, per capita real annual income decreases by \$18 on average, and gross world product drops by \$28 billion and on a 'once only' basis,

while \$51 billion of tax revenue is raised and 100 Mt of transported related CO₂ is abated cost-effectively each year. At this carbon price, the economic cost of reducing one tonne of CO₂ in the international aviation industry corresponds to \$280 in global value added.

In a combined policy scheme, where both the international maritime and aviation industry are subject to a carbon tax, the overall demand impact in each country is the sum of the demand impacts from both sectors.

While the price increases in trade are smaller, the impacts in terms of demand are larger as a result of relatively higher consumption and expenditure shares. Tourism is subject to larger price increases, with significant larger changes in domestic expenditures, while the demand impacts are smaller as a result of relatively smaller consumption and expenditure shares.

As the carbon revenue is not "recycled" within the system using a rebate mechanism, the predicted changes in real income in each country can be used towards determining patterns of discrimination against economically disadvantaged countries participating in the scheme. In international trade, no systematic pattern of discrimination against developing countries, SIDS, or LLDCs can be identified. In international tourism, no systematic pattern of discrimination against developing countries can be identified. As many of the SIDS are disproportionally dependent on international inbound tourism and as many of the LLDCs are geographically remote countries however, they would be systematically disadvantaged by a carbon emissions pricing scheme in the international aviation industry.

A carbon emissions pricing scheme in the international maritime industry would therefore be non-discriminatory and comply with the UNFCCC CBDR/RC principle and GATT *de jure* and *de facto* discriminatory regulations. In the international aviation industry, to comply with the UNFCCC CBDR/RC principle, SIDS and LLDCs would need to be exempt, as it is currently proposed by the ICAO for the CORSIA.

Carbon emissions pricing schemes in international transport could significantly contribute to the target of raising \$100 billion annually of global climate finance for developing countries under the UNFCCC umbrella in a post-Paris world. A carbon price of \$150/tCO₂ in international transport could raise all of the \$100 billion of global climate finance needed, while 318 Mt of transport related CO₂ could be abated cost-effectively each year. This scheme would result into a nonrecurring drop in gross world product of 0.13% and, except for SIDS, be non-discriminatory against developing countries.

Carbon emissions pricing schemes in international transport therefore pose a substantial opportunity to raise money for global climate finance. In comparison to an ETS, they are also administratively simple and ensure price stability. Given the tremendous challenges ahead in limiting the increase in the global average temperature to well below 2°C above pre-industrial levels and the inherently larger damages in terms of GWP if left unchecked,

the international transport industries could become a key enabler of global climate finance and open up ways to tackle the pressing issues lying ahead. A carbon emissions pricing scheme in international transport could therefore become a real game changer in international climate policy by strengthening the global response to the threat of climate change.

References

- Ahlfeldt, G. M., Redding, S. J., Sturm, D. M. and Wolf, N. (2015). ‘The Economics of Density: Evidence From the Berlin Wall’. In: *Econometrica* 83.6, pp. 2127–2189. ISSN: 1468-0262. DOI: 10.3982/ECTA10876. URL: <http://dx.doi.org/10.3982/ECTA10876>.
- Alchian, A. A. and Allen, W. R. (1967). *University economics*. Belmont: Wadsworth.
- Allen, T. (2014). ‘Information Frictions in Trade’. In: *Econometrica* 82.6, pp. 2041–2083. ISSN: 1468-0262. DOI: 10.3982/ECTA10984. URL: <http://dx.doi.org/10.3982/ECTA10984>.
- Allen, T. and Arkolakis, C. (2014). ‘Trade and the Topography of the Spatial Economy’. In: *The Quarterly Journal of Economics* 129.3, pp. 1085–1140. DOI: 10.1093/qje/qju016. eprint: <http://qje.oxfordjournals.org/content/129/3/1085.full.pdf+html>. URL: <http://qje.oxfordjournals.org/content/129/3/1085.abstract>.
- Alvik, S., Eide, M. S., Endresen, O., Hoffmann, P. and Longva, T. (2009). *Pathways to low carbon shipping-abatement potential towards 2030*. Report. Det Norske Veritas AS.
- Anderson, J. E. (1979). ‘A Theoretical Foundation for the Gravity Equation’. English. In: *The American Economic Review* 69.1, pp. 106–116. ISSN: 00028282. URL: <http://www.jstor.org/stable/1802501>.
- Anderson, J. E. and Wincoop, E. van (2003). ‘Gravity with Gravitas: A Solution to the Border Puzzle’. In: *American Economic Review* 93.1, pp. 170–192. DOI: 10.1257/000282803321455214. URL: <http://www.aeaweb.org/articles.php?doi=10.1257/000282803321455214>.
- (2004). *Trade Costs*. Working Paper 10480. National Bureau of Economic Research. DOI: 10.3386/w10480. URL: <http://www.nber.org/papers/w10480>.
- Anderson, J. E. and Yotov, Y. V. (2010). ‘The Changing Incidence of Geography’. In: *American Economic Review* 100.5, pp. 2157–86. DOI: 10.1257/aer.100.5.2157. URL: <http://www.aeaweb.org/articles?id=10.1257/aer.100.5.2157>.
- Anderson, S. P., De Palma, A. and Thisse, J. F. (1992). *Discrete choice theory of product differentiation*. MIT press.
- Anger, A. (2010). ‘Including aviation in the European emissions trading scheme: Impacts on the industry, CO2 emissions and macroeconomic activity in the EU’. In: *Journal of Air Transport Management* 16.2. Selected Papers from the Air Transport Research Society Conference Athens, 2008, pp. 100–105. ISSN: 0969-6997. DOI: <http://dx.doi.org/10.1016/j.jairtraman.2010.03.001>.

- org/10.1016/j.jairtraman.2009.10.009. URL: <http://www.sciencedirect.com/science/article/pii/S096969970900088X>.
- Antràs, P., Fort, T. C. and Tintelnot, F. (2017). ‘The Margins of Global Sourcing: Theory and Evidence from U.S. Firms’. In: *American Economic Review* 107.9.
- Antràs, P. and Helpman, E. (2004). ‘Global Sourcing’. In: *Journal of Political Economy* 112.3, pp. 552–580. DOI: 10.1086/383099. eprint: <http://dx.doi.org/10.1086/383099>. URL: <http://dx.doi.org/10.1086/383099>.
- Archer, B., Cooper, C. and Ruhanen, L. (2005). ‘Chapter 5 - The positive and negative impacts of tourism’. In: *Global Tourism (Third Edition)*. Ed. by W. F. Theobald. Third Edition. Boston: Butterworth-Heinemann, pp. 79–102. ISBN: 978-0-7506-7789-9. DOI: <http://dx.doi.org/10.1016/B978-0-7506-7789-9.50011-X>. URL: <http://www.sciencedirect.com/science/article/pii/B978075067789950011X>.
- Arkolakis, C., Costinot, A. and Rodríguez-Clare, A. (2012). ‘New Trade Models, Same Old Gains?’ In: *American Economic Review* 102.1, pp. 94–130. DOI: 10.1257/aer.102.1.94. URL: <http://www.aeaweb.org/articles.php?doi=10.1257/aer.102.1.94>.
- Arkolakis, C., Demidova, S., Klenow, P. J. and Rodríguez-Clare, A. (2008). ‘Endogenous Variety and the Gains from Trade’. In: *American Economic Review* 98.2, pp. 444–50. DOI: 10.1257/aer.98.2.444. URL: <http://www.aeaweb.org/articles?id=10.1257/aer.98.2.444>.
- Armington, P. S. (1969). ‘A Theory of Demand for Products Distinguished by Place of Production’. In: *Staff Papers-International Monetary Fund*, pp. 159–178.
- Artal-Tur, A., Pallardó-López, V. J. and Requena-Silvente, F. (2013). ‘Examining the impact of visa restrictions on international tourist flows using panel data’. In: *Fifteenth Annual ETSG Conference, Birmingham, 12-14 September 2013*. URL: <http://www.etsg.org/ETSG2013/Papers/111.pdf>.
- Baldwin, R. E. and Venables, A. J. (1995). ‘Chapter 31 Regional economic integration’. In: *Handbook of International Economics*. Vol. 3. Elsevier, pp. 1597–1644. DOI: [http://dx.doi.org/10.1016/S1573-4404\(05\)80011-5](http://dx.doi.org/10.1016/S1573-4404(05)80011-5). URL: <http://www.sciencedirect.com/science/article/pii/S1573440405800115>.
- Baldwin, R. and Taglioni, D. (2007). ‘Trade Effects of the Euro: a Comparison of Estimators’. In: *Journal of Economic Integration* 22.4, pp. 780–818. ISSN: 1225651X. URL: <http://www.jstor.org/stable/23000919>.
- Balli, F., Balli, H. O. and Louis, R. J. (2016). ‘The impacts of immigrants and institutions on bilateral tourism flows’. In: *Tourism Management* 52, pp. 221–229. ISSN: 0261-5177. DOI: <http://dx.doi.org/10.1016/j.tourman.2015.06.021>. URL: <http://www.sciencedirect.com/science/article/pii/S0261517715001454>.
- Bas, M., Mayer, T. and Thoenig, M. (2015). ‘From Micro to Macro: Demand, Supply, and Heterogeneity in the Trade Elasticity.’ In: URL: <http://dx.doi.org/10.2139/ssrn.2625937>.

- Ben-Akiva, M. and De Jong, G. (2013). 'The aggregate-disaggregate-aggregate (ADA) freight model system'. In: *Freight Transport Modelling*. Ed. by M. B. Akiva, H. Meersman and E. Van De Voorde. Emerald Group Publishing.
- Ben-Akiva, M. and Lerman, S. R. (1985). *Discrete choice analysis: theory and application to travel demand*. Vol. 9. MIT press.
- Bergstrand, J. H. (1985). 'The Gravity Equation in International Trade: Some Microeconomic Foundations and Empirical Evidence'. English. In: *The Review of Economics and Statistics* 67.3, pp. 474–481. ISSN: 00346535. URL: <http://www.jstor.org/stable/1925976>.
- Berkson, J. (1953). 'A Statistically Precise and Relatively Simple Method of Estimating the Bioassay with Quantal Response, Based on the Logistic Function'. English. In: *Journal of the American Statistical Association* 48.263, pp. 565–599. ISSN: 01621459. URL: <http://www.jstor.org/stable/2281010>.
- Bernard, A. B., Eaton, J., Jensen, J. B. and Kortum, S. (2003). 'Plants and Productivity in International Trade'. In: *American Economic Review* 93.4, pp. 1268–1290. DOI: 10.1257/000282803769206296. URL: <http://www.aeaweb.org/articles?id=10.1257/000282803769206296>.
- Bernard, A. B. and Jensen, J. B. (1999). 'Exceptional exporter performance: cause, effect, or both?' In: *Journal of International Economics* 47.1, pp. 1–25. ISSN: 0022-1996. DOI: [http://doi.org/10.1016/S0022-1996\(98\)00027-0](http://doi.org/10.1016/S0022-1996(98)00027-0). URL: <http://www.sciencedirect.com/science/article/pii/S0022199698000270>.
- Bernard, A. B., Jensen, J. B. and Lawrence, R. Z. (1995). 'Exporters, Jobs, and Wages in U.S. Manufacturing: 1976-1987'. In: *Brookings Papers on Economic Activity. Microeconomics* 1995, pp. 67–119. ISSN: 10578641. URL: <http://www.jstor.org/stable/2534772>.
- Bernard, A. B., Redding, S. J. and Schott, P. K. (2007). 'Comparative Advantage and Heterogeneous Firms'. In: *The Review of Economic Studies* 74.1, p. 31. DOI: 10.1111/j.1467-937X.2007.00413.x. eprint: /oup/backfile/Content_public/Journal/restud/74/1/10.1111/j.1467-937X.2007.00413.x/2/74-1-31.pdf. URL: <http://dx.doi.org/10.1111/j.1467-937X.2007.00413.x>.
- (2011). 'Multiproduct Firms and Trade Liberalization *'. In: *The Quarterly Journal of Economics* 126.3, p. 1271. DOI: 10.1093/qje/qjr021. eprint: /oup/backfile/Content_public/Journal/qje/126/3/10.1093_qje_qjr021/2/qjr021.pdf. URL: <http://dx.doi.org/10.1093/qje/qjr021>.
- Berry, S., Levinsohn, J. and Pakes, A. (1995). 'Automobile Prices in Market Equilibrium'. English. In: *Econometrica* 63.4, pp. 841–890. ISSN: 00129682. URL: <http://www.jstor.org/stable/2171802>.
- Bils, M. and Klenow, P. J. (2001). 'Quantifying Quality Growth'. In: *The American Economic Review* 91.4, pp. 1006–1030. ISSN: 00028282. URL: <http://www.jstor.org/stable/2677823>.

- Boeing (2014). *World Air Cargo Forecast 2014-2015*. URL: <http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/cargo-market-detail-wacf/download-report/assets/pdfs/wacf.pdf> (visited on 22/04/2016).
- Box, G. E. P. and Cox, D. R. (1964). 'An Analysis of Transformations'. In: *Journal of the Royal Statistical Society. Series B (Methodological)* 26.2, pp. 211–252. ISSN: 00359246. URL: <http://www.jstor.org/stable/2984418>.
- Broda, C., Greenfield, J. and Weinstein, D. (2006). *From Groundnuts to Globalization: A Structural Estimate of Trade and Growth*. Working Paper 12512. DOI: 10.3386/w12512. URL: <http://www.nber.org/papers/w12512>.
- Caliendo, L. and Parro, F. (2015). 'Estimates of the Trade and Welfare Effects of NAFTA'. In: *The Review of Economic Studies* 82.1, pp. 1–44. DOI: 10.1093/restud/rdu035. eprint: <http://restud.oxfordjournals.org/content/82/1/1.full.pdf+html>. URL: <http://restud.oxfordjournals.org/content/82/1/1.abstract>.
- Carey, H. C. (1858). *Principles of Social Science*. Philadelphia, Pennsylvania: J. Lippincott.
- Caves, D. W., Christensen, L. R. and Tretheway, M. W. (1984). 'Economies of Density versus Economies of Scale: Why Trunk and Local Service Airline Costs Differ'. In: *The RAND Journal of Economics* 15.4, pp. 471–489. ISSN: 07416261. URL: <http://www.jstor.org/stable/2555519>.
- Ceballos-Lascuráin, H. et al. (1996). *Tourism, ecotourism, and protected areas: The state of nature-based tourism around the world and guidelines for its development*. IUCN. ISBN: 2-8317-0124-4.
- Chandra, A., Head, K. and Tappata, M. (2014). 'The Economics of Cross-Border Travel'. In: *The Review of Economics and Statistics* 96.4, pp. 648–661. DOI: 10.1162/REST_a_00404. eprint: http://dx.doi.org/10.1162/REST_a_00404. URL: http://dx.doi.org/10.1162/REST_a_00404.
- Chaney, T. (2008). 'Distorted Gravity: The Intensive and Extensive Margins of International Trade'. In: *The American Economic Review* 98.4, pp. 1707–1721. DOI: doi: 10.1257/aer.98.4.1707. URL: <http://www.ingentaconnect.com/content/aea/aer/2008/00000098/00000004/art00024>.
- Clarkson Research Services (2014). *Shipping intelligence network*. URL: <https://sin.clarksons.net> (visited on 30/05/2014).
- Copeland, B. R. (1991). 'Tourism, Welfare and De-industrialization in a Small Open Economy'. In: *Economica* 58.232, pp. 515–529. ISSN: 00130427, 14680335. URL: <http://www.jstor.org/stable/2554696>.
- Corbett, J. J., Wang, H. and Winebrake, J. J. (2009). 'The effectiveness and costs of speed reductions on emissions from international shipping'. In: *Transportation Research Part D: Transport and Environment* 14.8, pp. 593–598. ISSN: 1361-9209. DOI: <http://dx.doi.org/10.1016/j.trd.2009.08.005>. URL: <http://www.sciencedirect.com/science/article/pii/S1361920909001072>.
- Costinot, A., Donaldson, D. and Komunjer, I. (2012). 'What Goods Do Countries Trade? A Quantitative Exploration of Ricardo's Ideas'. In: *The Review of Economic Studies* 79.2,

- pp. 581–608. DOI: 10.1093/restud/rdr033. eprint: <http://restud.oxfordjournals.org/content/79/2/581.full.pdf+html>. URL: <http://restud.oxfordjournals.org/content/79/2/581.abstract>.
- Costinot, A., Donaldson, D. and Smith, C. (2016). ‘Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from 1.7 Million Fields around the World’. In: *Journal of Political Economy* 124.1, pp. 205–248. DOI: 10.1086/684719. eprint: <http://dx.doi.org/10.1086/684719>. URL: <http://dx.doi.org/10.1086/684719>.
- Costinot, A. and Rodríguez-Clare, A. (2014). ‘Chapter 4 - Trade Theory with Numbers: Quantifying the Consequences of Globalization’. In: *Handbook of International Economics*. Ed. by E. H. Gita Gopinath and K. Rogoff. Vol. 4. Elsevier, pp. 197–261. DOI: <http://dx.doi.org/10.1016/B978-0-444-54314-1.00004-5>. URL: <http://www.sciencedirect.com/science/article/pii/B9780444543141000045>.
- Cox, D. R. and Snell, E. J. (1989). *Analysis of binary data*. Vol. 32. CRC Press.
- Cristea, A., Hummels, D., Puzzello, L. and Avetisyan, M. (2013). ‘Trade and the greenhouse gas emissions from international freight transport’. In: *Journal of Environmental Economics and Management* 65.1, pp. 153–173. ISSN: 0095-0696. DOI: <http://dx.doi.org/10.1016/j.jeem.2012.06.002>. URL: <http://www.sciencedirect.com/science/article/pii/S0095069612000708>.
- De Borger, B. and Nonneman, W. (1981). ‘Statistical Cost Functions for Dry Bulk Carriers’. In: *Journal of Transport Economics and Policy* 15.2, pp. 155–165. ISSN: 00225258. URL: <http://www.jstor.org/stable/20052610>.
- De Jong, G. (2008). ‘Value of freight travel-time savings’. In: *Handbook of Transport Modelling (2nd Edition)*. Emerald, Inc., pp. 649–663.
- De Jong, G., Daly, A., Pieters, M. and Van der Hoorn, T. (2007). ‘The logsum as an evaluation measure: Review of the literature and new results’. In: *Transportation Research Part A: Policy and Practice* 41.9. Selected Papers on Applications of Discrete Choice Models Presented at the European Regional Science Conference, Amsterdam, August 2005, pp. 874–889. ISSN: 0965-8564. DOI: <http://dx.doi.org/10.1016/j.tra.2006.10.002>. URL: <http://www.sciencedirect.com/science/article/pii/S0965856407000316>.
- Deardorff, A. (1998). ‘Determinants of bilateral trade: does gravity work in a neoclassical world?’ In: *The regionalization of the world economy*. University of Chicago Press, pp. 7–32.
- Dekle, R., Eaton, J. and Kortum, S. (2008). ‘Global rebalancing with gravity: measuring the burden of adjustment’. In: *IMF Staff Papers* 55.3, pp. 511–540. DOI: [doi:10.1057/imfsp.2008.17](https://doi.org/10.1057/imfsp.2008.17). URL: <https://www.imf.org/External/Pubs/FT/staffp/2008/03/pdf/dekle.pdf>.
- DeSerpa, A. C. (1971). ‘A Theory of the Economics of Time’. English. In: *The Economic Journal* 81.324, pp. 828–846. ISSN: 00130133. URL: <http://www.jstor.org/stable/2230320>.

- Donaldson, D. (2010). *Railroads of the Raj: Estimating the Impact of Transportation Infrastructure*. Working Paper 16487. DOI: 10.3386/w16487. URL: <http://www.nber.org/papers/w16487>.
- Dornbusch, R., Fischer, S. and Samuelson, P. A. (1977). ‘Comparative Advantage, Trade, and Payments in a Ricardian Model with a Continuum of Goods’. In: *The American Economic Review* 67.5, pp. 823–839. ISSN: 00028282. URL: <http://www.jstor.org/stable/1828066>.
- Dray, L., Evans, A., Reynolds, T., Rogers, H., Schäfer, A. and Vera-Morales, M. (2009). ‘Air transport within an emissions trading regime: a network-based analysis of the United States and India’. In: *TRB 88th Annual Meeting, Washington DC*, pp. 11–15.
- Eaton, J. and Kortum, S. (1997). *Technology and Bilateral Trade*. Working Paper 6253. National Bureau of Economic Research. DOI: 10.3386/w6253. URL: <http://www.nber.org/papers/w6253>.
- (2002). ‘Technology, Geography, and Trade’. In: *Econometrica* 70.5, pp. 1741–1779. ISSN: 1468-0262. DOI: 10.1111/1468-0262.00352. URL: <http://dx.doi.org/10.1111/1468-0262.00352>.
- EC (2017a). *Reducing emissions from aviation*. European Commission. URL: https://ec.europa.eu/clima/policies/transport/aviation_en (visited on 14/05/2017).
- (2017b). *Reducing emissions from the shipping sector*. European Commission. URL: https://ec.europa.eu/clima/policies/transport/shipping_en (visited on 14/05/2017).
- Economist, T. (2012). *Complete Disaster in the Making*.
- EIA (2017). *U.S. Energy Information Administration*. URL: <https://www.eia.gov/petroleum/data.php#prices> (visited on 22/05/2017).
- Eurostat (2014). *User guide on European statistics on international trade in goods*. Manual ISSN 2315-0815. European Union. DOI: 10.2785/514986. URL: <http://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/KS-GQ-14-014> (visited on 10/02/2015).
- (2015). *European external trade data Comext*. URL: <http://ec.europa.eu/eurostat/data/bulkdownload> (visited on 09/06/2015).
- Faber, B. and Gaubert, C. (2016). *Tourism and Economic Development: Evidence from Mexico’s Coastline*. Working Paper 22300. National Bureau of Economic Research. DOI: 10.3386/w22300. URL: <http://www.nber.org/papers/w22300>.
- Fajgelbaum, P., Grossman, G. M. and Helpman, E. (2011). ‘Income Distribution, Product Quality, and International Trade’. In: *Journal of Political Economy* 119.4, pp. 721–765. DOI: 10.1086/662628. eprint: <http://dx.doi.org/10.1086/662628>. URL: <http://dx.doi.org/10.1086/662628>.
- Fally, T. (2015). ‘Structural gravity and fixed effects’. In: *Journal of International Economics* 97.1, pp. 76–85. ISSN: 0022-1996. DOI: <http://dx.doi.org/10.1016/j.jinteco.2015.05.005>. URL: <http://www.sciencedirect.com/science/article/pii/S0022199615001026>.

- Faye, M. L., McArthur, J. W., Sachs, J. D. and Snow, T. (2004). 'The Challenges Facing Landlocked Developing Countries'. In: *Journal of Human Development* 5.1, pp. 31–68. DOI: 10.1080/14649880310001660201. eprint: <http://dx.doi.org/10.1080/14649880310001660201>. URL: <http://dx.doi.org/10.1080/14649880310001660201>.
- Feenstra, R. C. (1994). 'New Product Varieties and the Measurement of International Prices'. English. In: *The American Economic Review* 84.1, pp. 157–177. ISSN: 00028282. URL: <http://www.jstor.org/stable/2117976>.
- (2003a). 'A homothetic utility function for monopolistic competition models, without constant price elasticity'. In: *Economics Letters* 78.1, pp. 79–86. ISSN: 0165-1765. DOI: [http://dx.doi.org/10.1016/S0165-1765\(02\)00181-7](http://dx.doi.org/10.1016/S0165-1765(02)00181-7). URL: <http://www.sciencedirect.com/science/article/pii/S0165176502001817>.
- (2003b). *Advanced international trade: theory and evidence*. Princeton University Press.
- Fischer, T. and Kamerschen, D. R. (2003). 'Price-Cost Margins in the US Airline Industry Using a Conjectural Variation Approach'. English. In: *Journal of Transport Economics and Policy* 37.2, pp. 227–259. ISSN: 00225258. URL: <http://www.jstor.org/stable/20053932>.
- Frechtling, D. C. (2010). 'The Tourism Satellite Account: A Primer'. In: *Annals of Tourism Research* 37.1, pp. 136–153. ISSN: 0160-7383. DOI: <http://dx.doi.org/10.1016/j.annals.2009.08.003>. URL: <http://www.sciencedirect.com/science/article/pii/S0160738309000991>.
- Gallagher, K. P. and Taylor, R. (2003). 'International Trade and Air Pollution: The Economic Costs of Air Emissions from Waterborne Commerce Vessels in the United States'. In: URL: http://www.ase.tufts.edu/Gdae/publications/working_papers/03-08WaterborneCommerce.PDF.
- Gillen, D. W., Oum, T. H. and Tretheway, M. W. (1990). 'Airline Cost Structure and Policy Implications: A Multi-Product Approach for Canadian Airlines'. English. In: *Journal of Transport Economics and Policy* 24.1, pp. 9–34. ISSN: 00225258. URL: <http://www.jstor.org/stable/20052902>.
- Greene, W. H. (2002). *Econometric analysis*. Pearson Education India.
- Grubb, M. (2014). *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge.
- Grubb, M., Sha, F., Spencer, T., Hughes, N., Zhang, Z. and Agnolucci, P. (2015). 'A review of Chinese CO2 emission projections to 2030: the role of economic structure and policy'. In: *Climate Policy* 15.sup1, S7–S39. DOI: 10.1080/14693062.2015.1101307. eprint: <http://dx.doi.org/10.1080/14693062.2015.1101307>. URL: <http://dx.doi.org/10.1080/14693062.2015.1101307>.
- Gucwa, M. and Schäfer, A. (2013). 'The impact of scale on energy intensity in freight transportation'. In: *Transportation Research Part D: Transport and Environment* 23.0, pp. 41–49. ISSN: 1361-9209. DOI: <http://dx.doi.org/10.1016/j.trd.2013.03.008>.
- Guerrero, V. M. and Johnson, R. A. (1982). 'Use of the Box-Cox transformation with binary response models'. In: *Biometrika* 69.2, pp. 309–314. DOI: 10.1093/biomet/69.2.309.

- eprint: <http://biomet.oxfordjournals.org/content/69/2/309.full.pdf+html>.
 URL: <http://biomet.oxfordjournals.org/content/69/2/309.abstract>.
- Hanson, G. H. and Xiang, C. (2004). ‘The Home-Market Effect and Bilateral Trade Patterns’. In: *American Economic Review* 94.4, pp. 1108–1129. DOI: 10.1257/0002828042002688. URL: <http://www.aeaweb.org/articles?id=10.1257/0002828042002688>.
- Harrigan, J. (1995). ‘The Volume of Trade in Differentiated Intermediate Goods: Theory and Evidence’. English. In: *The Review of Economics and Statistics* 77.2, pp. 283–293. ISSN: 00346535. URL: <http://www.jstor.org/stable/2109865>.
- (2010). ‘Airplanes and comparative advantage’. In: *Journal of International Economics* 82.2, pp. 181–194. ISSN: 0022-1996. DOI: <http://dx.doi.org/10.1016/j.jinteco.2010.07.002>. URL: <http://www.sciencedirect.com/science/article/pii/S0022199610000644>.
- Head, K. and Mayer, T. (2000). ‘Non-Europe: The Magnitude and Causes of Market Fragmentation in the EU’. In: *Weltwirtschaftliches Archiv* 136.2, pp. 284–314. ISSN: 00432636. URL: <http://www.jstor.org/stable/40440779>.
- (2013). ‘What separates us? Sources of resistance to globalization’. In: *Canadian Journal of Economics/Revue canadienne d’économie* 46.4, pp. 1196–1231. ISSN: 1540-5982. DOI: 10.1111/caje.12055. URL: <http://dx.doi.org/10.1111/caje.12055>.
- (2014). ‘Chapter 3 - Gravity Equations: Workhorse, Toolkit, and Cookbook’. In: *Handbook of International Economics*. Ed. by K. R. Elhanan Helpman and G. Gopinath. Vol. 4. Elsevier, pp. 131–195. DOI: <http://dx.doi.org/10.1016/B978-0-444-54314-1.00003-3>. URL: <http://www.sciencedirect.com/science/article/pii/B9780444543141000033>.
- Head, K. and Ries, J. (2001). ‘Increasing Returns versus National Product Differentiation as an Explanation for the Pattern of U.S.-Canada Trade’. In: *The American Economic Review* 91.4, pp. 858–876. ISSN: 00028282. URL: <http://www.jstor.org/stable/2677816>.
- Heckscher, E. F. (1919). *The effect of foreign trade on the distribution of income*. Ekonomisk Tidskrift, pp. 497–512.
- Helpman, E. (1981). ‘International trade in the presence of product differentiation, economies of scale and monopolistic competition’. In: *Journal of International Economics* 11.3, pp. 305–340. ISSN: 0022-1996. DOI: [http://dx.doi.org/10.1016/0022-1996\(81\)90001-5](http://dx.doi.org/10.1016/0022-1996(81)90001-5). URL: <http://www.sciencedirect.com/science/article/pii/0022199681900015>.
- (1987). ‘Imperfect competition and international trade: Evidence from fourteen industrial countries’. In: *Journal of the Japanese and International Economies* 1.1, pp. 62–81. ISSN: 0889-1583. DOI: [http://dx.doi.org/10.1016/0889-1583\(87\)90027-X](http://dx.doi.org/10.1016/0889-1583(87)90027-X). URL: <http://www.sciencedirect.com/science/article/pii/088915838790027X>.
- (2011). *Understanding Global Trade*. Harvard University Press. ISBN: 9780674060784. URL: <http://www.jstor.org/stable/j.ctt24hhh9>.

- Helpman, E., Melitz, M. J. and Rubinstein, Y. (2008). ‘Estimating Trade Flows: Trading Partners and Trading Volumes’. In: *The Quarterly Journal of Economics* 123.2, pp. 441–487. DOI: 10.1162/qjec.2008.123.2.441. eprint: <http://qje.oxfordjournals.org/content/123/2/441.full.pdf+html>. URL: <http://qje.oxfordjournals.org/content/123/2/441.abstract>.
- Hummels, D. (1999). ‘Toward a geography of trade costs’. In: *GTAP Papers*, p. 17.
- (2007). ‘Transportation costs and international trade in the second era of globalization’. In: *The Journal of Economic Perspectives* 21.3, pp. 131–154.
- Hummels, D. L. and Schaur, G. (2013). ‘Time as a Trade Barrier’. In: *American Economic Review* 103.7, pp. 2935–59. DOI: 10.1257/aer.103.7.2935. URL: <http://www.aeaweb.org/articles.php?doi=10.1257/aer.103.7.2935>.
- Hummels, D. and Lugovskyy, V. (2006). ‘Are Matched Partner Trade Statistics a Usable Measure of Transportation Costs?’*. In: *Review of International Economics* 14.1, pp. 69–86. ISSN: 1467-9396. DOI: 10.1111/j.1467-9396.2006.00561.x. URL: <http://dx.doi.org/10.1111/j.1467-9396.2006.00561.x>.
- Hummels, D. and Skiba, A. (2004). ‘Shipping the Good Apples Out? An Empirical Confirmation of the Alchian-Allen Conjecture’. In: *Journal of Political Economy* 112.6, pp. 1384–1402. ISSN: 00223808, 1537534X. URL: <http://www.jstor.org/stable/10.1086/422562>.
- ICAO (2006). *Convention on International Civil Aviation*. Tech. rep. URL: https://www.icao.int/publications/Documents/7300_9ed.pdf.
- (2014). *Annual Report of the ICAO Council - The World of Air Transport in 2014*. URL: http://www.icao.int/annual-report-2014/Documents/Appendix_1_en.pdf (visited on 04/05/2017).
- (2016). *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*. URL: <https://www.icao.int/environmental-protection/Pages/market-based-measures.aspx> (visited on 24/05/2016).
- ICS (2017). *International Chamber of Shipping. Annual review 2017*. Report. URL: <http://www.ics-shipping.org/docs/default-source/ICS-Annual-Review-2017/ics-annual-review-2017.pdf?sfvrsn=10>.
- IEA (2015). *CO2 Emissions from Fuel Combustion - Highlights*. International Energy Agency. URL: <http://www.iea.org/publications/> (visited on 22/04/2016).
- IMO (2011a). *Reduction of GHG emissions from ships. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures*. Report MEPC 62/INF.7. International Maritime Organization, London, UK.
- (2011b). *Reduction of GHG emissions from ships. Report of the third intersessional meeting of the working group on greenhouse gas emissions from ships. Note by the secretariat*. Report MEPC 62/5/1. International Maritime Organization, London, UK.
- (2012). *Resolution MEPC.212(63)*. Report MEPC 63/23, Annex 8. International Maritime Organization, London, UK. URL: [http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/212\(63\).pdf](http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/212(63).pdf) (visited on 30/03/2017).

- IMO (2014). *Third IMO GHG Study 2014*. Report MEPC 67/INF.3. International Maritime Organization, London, UK; Smith, T.W.P.; Jalkanen, J.P.; Anderson, B.A.; et al. URL: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Relevant-links-to-Third-IMO-GHG-Study-2014.aspx> (visited on 09/04/2015).
- (2015). *The Existing Shipping Fleet's CO₂ Efficiency*. Report MEPC 68/INF.24. International Maritime Organization (IMO), London, UK; Smith, T.W.P.; Prakash, V.; Aldous, L.; Krammer, P. URL: <https://docs.imo.org>.
- (2016). *Documentation of the Marine Environment Protection Committee (MEPC), 69th session, 18-22 April 2016*. URL: <http://www.imo.org/en/MediaCentre/MeetingSummaries/MEPC/Pages/MEPC-69th-session.aspx> (visited on 24/05/2016).
- (2017). *Convention on the International Maritime Organization*. URL: <http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/Convention-on-the-International-Maritime-Organization.aspx> (visited on 13/05/2017).
- Jamin, S., Schäfer, A., Ben-Akiva, M. E. and Waitz, I. A. (2004). 'Aviation emissions and abatement policies in the United States: a city-pair analysis'. In: *Transportation Research Part D: Transport and Environment* 9.4, pp. 295–317. ISSN: 1361-9209. DOI: <http://doi.org/10.1016/j.trd.2004.03.001>. URL: <http://www.sciencedirect.com/science/article/pii/S1361920904000227>.
- Johnston, A. and Ozment, J. (2013). 'Economies of scale in the {US} airline industry'. In: *Transportation Research Part E: Logistics and Transportation Review* 51, pp. 95–108. ISSN: 1366-5545. DOI: <http://dx.doi.org/10.1016/j.tre.2012.09.002>. URL: <http://www.sciencedirect.com/science/article/pii/S136655451200083X>.
- Kay, R. and Little, S. (1987). 'Transformations of the explanatory variables in the logistic regression model for binary data'. In: *Biometrika* 74.3, pp. 495–501. DOI: 10.1093/biomet/74.3.495. eprint: <http://biomet.oxfordjournals.org/content/74/3/495.full.pdf+html>. URL: <http://biomet.oxfordjournals.org/content/74/3/495.abstract>.
- Keen, M., Parry, I. and Strand, J. (2013). 'Planes, ships and taxes: charging for international aviation and maritime emissions'. In: *Economic Policy* 28.76, pp. 701–749. DOI: 10.1111/1468-0327.12019. eprint: <http://economicpolicy.oxfordjournals.org/content/28/76/701.full.pdf>. URL: <http://economicpolicy.oxfordjournals.org/content/28/76/701>.
- Keum, K. (2008). 'Tourism flows and trade theory: a panel data analysis with the gravity model'. In: *The Annals of Regional Science* 44.3, pp. 541–557. ISSN: 1432-0592. DOI: 10.1007/s00168-008-0275-2. URL: <http://dx.doi.org/10.1007/s00168-008-0275-2>.
- Korinek, J. (2011). 'Clarifying trade costs in maritime transport'. In: *Organization for Economic Co-operation and Development TAD/TC/WP (2008)* 10.
- Kroo, I. and Shevell, R. (2001). *Aircraft design: Synthesis and analysis*. Tech. rep. Desktop Aeronautics Inc., Textbook Version 0.99. URL: <http://adg.stanford.edu/aa241/>.

- Krugman, P. (1979). ‘Increasing returns, monopolistic competition, and international trade’. In: *Journal of International Economics* 9.4, pp. 469–479. ISSN: 0022-1996. DOI: [http://dx.doi.org/10.1016/0022-1996\(79\)90017-5](http://dx.doi.org/10.1016/0022-1996(79)90017-5). URL: <http://www.sciencedirect.com/science/article/pii/0022199679900175>.
- (1980). ‘Scale Economies, Product Differentiation, and the Pattern of Trade’. English. In: *The American Economic Review* 70.5, pp. 950–959. ISSN: 00028282. URL: <http://www.jstor.org/stable/1805774>.
- (1991). *Geography and trade*. MIT press.
- (1995). ‘Chapter 24 Increasing returns, imperfect competition and the positive theory of international trade’. In: *Handbook of International Economics*. Ed. by G. M. Grossman and K. Rogoff. Vol. 3. Elsevier, pp. 1243–1277. DOI: [http://dx.doi.org/10.1016/S1573-4404\(05\)80004-8](http://dx.doi.org/10.1016/S1573-4404(05)80004-8). URL: <http://www.sciencedirect.com/science/article/pii/S1573440405800048>.
- Leamer, E. E. and Levinsohn, J. (1995). ‘Chapter 26 International trade theory: The evidence’. In: *Handbook of International Economics*. Ed. by G. M. Grossman and K. Rogoff. Vol. 3. Elsevier, pp. 1339–1394. DOI: [http://dx.doi.org/10.1016/S1573-4404\(05\)80006-1](http://dx.doi.org/10.1016/S1573-4404(05)80006-1). URL: <http://www.sciencedirect.com/science/article/pii/S1573440405800061>.
- Limão, N. and Venables, A. J. (2001). ‘Infrastructure, Geographical Disadvantage, Transport Costs, and Trade’. In: *The World Bank Economic Review* 15.3, pp. 451–479. DOI: 10.1093/wber/15.3.451. eprint: <http://wber.oxfordjournals.org/content/15/3/451.full.pdf+html>. URL: <http://wber.oxfordjournals.org/content/15/3/451.abstract>.
- Lucas, R. E. and Rossi-Hansberg, E. (2002). ‘On the Internal Structure of Cities’. In: *Econometrica* 70.4, pp. 1445–1476. ISSN: 1468-0262. DOI: 10.1111/1468-0262.00338. URL: <http://dx.doi.org/10.1111/1468-0262.00338>.
- Lundmark, R. and Söderholm, P. (2004). ‘Estimating and decomposing the rate of technical change in the Swedish pulp and paper industry: A general index approach’. In: *International Journal of Production Economics* 91.1, pp. 17–35. ISSN: 0925-5273. DOI: [http://dx.doi.org/10.1016/S0925-5273\(03\)00203-2](http://dx.doi.org/10.1016/S0925-5273(03)00203-2). URL: <http://www.sciencedirect.com/science/article/pii/S0925527303002032>.
- Lux, M. (2011). *Defying gravity: The substitutability of transportation in international trade*. Tech. rep.
- Maneschi, A. (2009). ‘Comparative Advantage’. In: Reinert, K. A. and Rajan, R. S. *The Princeton Encyclopedia of the World Economy*. Princeton, New Jersey: Princeton University Press.
- Martinez, L., Kaupila, J. and Gachassin, M. C. (2014). ‘International Freight and Related CO2 Emissions by 2050: A New Modelling Tool’. In: DOI: <http://dx.doi.org/10.1787/5jrw1kslrm9t-en>. URL: [/content/workingpaper/5jrw1kslrm9t-en](http://content.workingpaper/5jrw1kslrm9t-en).
- Mathieson, A., Wall, G. et al. (1982). *Tourism, economic, physical and social impacts*. Prentice Hall. ISBN: 978-0582300613.

- Matteo, L. D. and Matteo, R. D. (1996). 'An analysis of Canadian cross-border travel'. In: *Annals of Tourism Research* 23.1, pp. 103–122. ISSN: 0160-7383. DOI: [http://dx.doi.org/10.1016/0160-7383\(95\)00038-0](http://dx.doi.org/10.1016/0160-7383(95)00038-0). URL: <http://www.sciencedirect.com/science/article/pii/0160738395000380>.
- Mayer, T. and Thoenig, M. (2016). *Regional Trade Agreements and the Pacification of Eastern Africa*. Working Paper. URL: <http://www.theigc.org/wp-content/uploads/2016/06/Mayer-and-Thoenig-2016-Working-paper.pdf>.
- Mayer, T. and Zignago, S. (2011). *Notes on CEPII's distances measures: The GeoDist database*. Working Papers 2011-25. CEPII. URL: <http://www.cepii.fr/CEPII/en/publications/wp/abstract.asp?NoDoc=3877>.
- McCallum, J. (1995). 'National borders matter: Canada-US regional trade patterns'. In: *The American Economic Review*, pp. 615–623.
- McFadden, D. (1973). 'Conditional logit analysis of qualitative choice behavior'. In: *Frontiers in Econometrics*, pp. 105–142.
- Melitz, M. J. (2003). 'The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity'. In: *Econometrica* 71.6, pp. 1695–1725. ISSN: 1468-0262. DOI: 10.1111/1468-0262.00467. URL: <http://dx.doi.org/10.1111/1468-0262.00467>.
- Melitz, M. J. and Ottaviano, G. I. P. (2008). 'Market Size, Trade, and Productivity'. In: *The Review of Economic Studies* 75.1, pp. 295–316. DOI: 10.1111/j.1467-937X.2007.00463.x. eprint: <http://restud.oxfordjournals.org/content/75/1/295.full.pdf+html>. URL: <http://restud.oxfordjournals.org/content/75/1/295.abstract>.
- Melitz, M. J. and Redding, S. J. (2015). 'New Trade Models, New Welfare Implications'. In: *American Economic Review* 105.3, pp. 1105–46. DOI: 10.1257/aer.20130351. URL: <http://www.aeaweb.org/articles?id=10.1257/aer.20130351>.
- Moore Stephens LLP (2015). *OpCost*. URL: <https://opcost.moorestephens.org/> (visited on 21/08/2015).
- Neumayer, E. (2010). 'Visa Restrictions and Bilateral Travel'. In: *The Professional Geographer* 62.2, pp. 171–181. DOI: 10.1080/00330121003600835. eprint: <http://dx.doi.org/10.1080/00330121003600835>. URL: <http://dx.doi.org/10.1080/00330121003600835>.
- (2011). 'On the detrimental impact of visa restrictions on bilateral trade and foreign direct investment'. In: *Applied Geography* 31.3, pp. 901–907. ISSN: 0143-6228. DOI: <http://dx.doi.org/10.1016/j.apgeog.2011.01.009>. URL: <http://www.sciencedirect.com/science/article/pii/S0143622811000105>.
- Newton, S. (2009). *Worldnet Final Report D11 of the consortium OSC, IWW, MKMETRIC, TINA Vienna and DEMIS. European Sixth Framework Programme*. Tech. rep. <http://www.etisplus.eu/documents/Public/ArchiveWorldnet/>, accessed 2015-01-19. NEA. URL: <http://www.etisplus.eu/documents/Public/Archive%20Worldnet/> (visited on 19/01/2015).
- Nordhaus, W. D. (1994). *Managing the global commons: the economics of climate change*. Vol. 31. MIT press Cambridge, MA.

- Novy, D. (2013). 'International trade without CES: Estimating translog gravity'. In: *Journal of International Economics* 89.2, pp. 271–282. ISSN: 0022-1996. DOI: <http://dx.doi.org/10.1016/j.jinteco.2012.08.010>. URL: <http://www.sciencedirect.com/science/article/pii/S0022199612001584>.
- Nunn, N. and Puga, D. (2012). 'Ruggedness: The Blessing of Bad Geography in Africa'. In: *Review of Economics and Statistics* 94.1, pp. 20–36.
- OECD (2007). *Maritime Transport Costs database*. URL: <https://stats.oecd.org/Index.aspx?DataSetCode=MTC#> (visited on 17/07/2016).
- (2012). 'OECD Tourism Trends and Policies 2012'. In: DOI: <http://dx.doi.org/10.1787/tour-2012-en>. URL: </content/book/tour-2012-en>.
- (2016). *Measuring Trade in Value Added: An OECD-WTO joint initiative*. URL: <http://www.oecd.org/sti/ind/measuringtradeinvalue-addedanoecd-wtojointinitiative.htm> (visited on 25/07/2016).
- (2017a). *OECD Input-Output Tables*. URL: <http://www.oecd.org/trade/input-outputtables.htm>.
- (2017b). *Productivity and ULC by main economic activity*. URL: http://stats.oecd.org/Index.aspx?DataSetCode=PDBI_I4# (visited on 01/02/2017).
- OECD ITF (2015). 'International freight and CO2 emissions to 2050'. In: *ITF Transport Outlook 2015*. Ed. by OECD. OECD Publishing, Paris/ITF, Paris. DOI: <http://dx.doi.org/10.1787/9789282107782-7-en>. URL: </content/chapter/9789282107782-7-en>.
- Ohlin, B. (1935). 'Interregional and international trade'. In:
- Oum, T. H. and Yu, C. (1998). 'Cost competitiveness of major airlines: an international comparison'. In: *Transportation Research Part A: Policy and Practice* 32.6, pp. 407–422. ISSN: 0965-8564. DOI: [http://dx.doi.org/10.1016/S0965-8564\(98\)00007-X](http://dx.doi.org/10.1016/S0965-8564(98)00007-X). URL: <http://www.sciencedirect.com/science/article/pii/S096585649800007X>.
- Panagariya, A. (2009). 'Heckscher-Ohlin model'. In: Reinert, K. A. and Rajan, R. S. *The Princeton Encyclopedia of the World Economy*. Princeton, New Jersey: Princeton University Press.
- Papke, L. E. and Wooldridge, J. M. (1996). 'Econometric Methods for Fractional Response Variables With an Application to 401 (K) Plan Participation Rates'. In: *Journal of Applied Econometrics* 11.6, pp. 619–632. ISSN: 08837252, 10991255. URL: <http://www.jstor.org/stable/2285155>.
- Penner, J. E. (1999). *Aviation and the global atmosphere: A special report of IPCC Working Groups I and III in collab. with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer*. Cambridge: Cambridge University Press. ISBN: 0521664047.
- Pierce, J. R. and Schott, P. K. (2016). 'The Surprisingly Swift Decline of US Manufacturing Employment'. In: *American Economic Review* 106.7, pp. 1632–62. DOI: 10.1257/aer.20131578. URL: <http://www.aeaweb.org/articles?id=10.1257/aer.20131578>.

- Pongas, E. (2006). *Statistics in Focus: Extra EU-25 trade in goods by mode of transport*. Report KS-NO-06-002. Eurostat, European Union. URL: <http://ec.europa.eu/eurostat/web/products-statistics-in-focus/-/KS-NO-06-002> (visited on 10/02/2015).
- Portland State University Economics Department (2016). *Country Geography Data*. URL: <https://www.pdx.edu/econ/country-geography-data>.
- Prakash, V. (forthcoming). 'Emissions, efficiency, and shipping markets.' PhD dissertation, Energy Institute, University College London.
- Redding, S. J. and Rossi-Hansberg, E. (2017). 'Quantitative Spatial Economics'. In: *Annual Review of Economics* 9.1, pp. 21–58. DOI: 10.1146/annurev-economics-063016-103713. eprint: <https://doi.org/10.1146/annurev-economics-063016-103713>. URL: <https://doi.org/10.1146/annurev-economics-063016-103713>.
- Redding, S. and Venables, A. J. (2004). 'Economic geography and international inequality'. In: *Journal of International Economics* 62.1, pp. 53–82. ISSN: 0022-1996. DOI: <http://dx.doi.org/10.1016/j.jinteco.2003.07.001>. URL: <http://www.sciencedirect.com/science/article/pii/S0022199603000965>.
- Reynolds, T. G., Barrett, S., Dray, L., Evans, A., Köhler, M., Morales, M. V., Schäfer, A., Wadud, Z., Britter, R., Hallam, H. et al. (2007). 'Modelling environmental and economic impacts of aviation: Introducing the aviation integrated modelling project'. In: *7th AIAA aviation technology, integration and operations conference*.
- Sabre (2016). *Airport Data Intelligence*. URL: http://www.sabreairlinesolutions.com/home/software_solutions/airports/ (visited on 30/05/2016).
- Sampson, T. (2016). 'Dynamic Selection: An Idea Flows Theory of Entry, Trade, and Growth *'. In: *The Quarterly Journal of Economics* 131.1, p. 315. DOI: 10.1093/qje/qjv032. eprint: /oup/backfile/Content_public/Journal/qje/131/1/10.1093_qje_qjv032/1/qjv032.pdf. URL: <http://dx.doi.org/10.1093/qje/qjv032>.
- Samuelson, P. A. (1948). 'International trade and the equalisation of factor prices'. In: *The Economic Journal* 58.230, pp. 163–184.
- (1954). 'The transfer problem and transport costs, II: Analysis of effects of trade impediments'. In: *The Economic Journal* 64.254, pp. 264–289.
- Schäfer, A. (2015). 'Long-term trends in domestic US passenger travel: the past 110 years and the next 90'. English. In: *Transportation*, pp. 1–18. ISSN: 0049-4488. DOI: 10.1007/s11116-015-9638-6. URL: <http://dx.doi.org/10.1007/s11116-015-9638-6>.
- Schäfer, A. W., Evans, A. D., Reynolds, T. G. and Dray, L. (2015). 'Costs of mitigating CO2 emissions from passenger aircraft'. In: *Nature Climate Change*.
- Schäfer, A., Heywood, J. B., Jacoby, H. D. and Waitz, I. A. (2009). *Transportation in a climate-constrained world*. MIT press. ISBN: 9780262012676.
- Scheelhaase, J. D. and Grimme, W. G. (2007). 'Emissions trading for international aviation—an estimation of the economic impact on selected European airlines'. In: *Journal of Air Transport Management* 13.5. The Air Transport Research Society's 10th year Anniversary, Nagoya Conference, 2006, pp. 253–263. ISSN: 0969-6997. DOI: <https://>

- doi.org/10.1016/j.jairtraman.2007.04.010. URL: <http://www.sciencedirect.com/science/article/pii/S0969699707000440>.
- Schott, P. K. (2004). 'Across-Product versus Within-Product Specialization in International Trade'. In: *The Quarterly Journal of Economics* 119.2, pp. 647–678. ISSN: 00335533, 15314650. URL: <http://www.jstor.org/stable/25098696>.
- Shapiro, J. S. (2016). 'Trade Costs, CO₂, and the Environment'. In: *American Economic Journal: Economic Policy* 8.4, pp. 220–54. DOI: 10.1257/pol.20150168. URL: <http://www.aeaweb.org/articles?id=10.1257/pol.20150168>.
- Sharpley, R. (2000). 'Tourism and Sustainable Development: Exploring the Theoretical Divide'. In: *Journal of Sustainable Tourism* 8.1, pp. 1–19. DOI: 10.1080/09669580008667346. eprint: <http://dx.doi.org/10.1080/09669580008667346>. URL: <http://dx.doi.org/10.1080/09669580008667346>.
- Silva, J. S. and Tenreyro, S. (2006). 'The log of gravity'. In: *The Review of Economics and Statistics* 88.4, pp. 641–658.
- Simonovska, I. and Waugh, M. E. (2014). 'The elasticity of trade: Estimates and evidence'. In: *Journal of International Economics* 92.1, pp. 34–50. ISSN: 0022-1996. DOI: <http://dx.doi.org/10.1016/j.jinteco.2013.10.001>. URL: <http://www.sciencedirect.com/science/article/pii/S0022199613000986>.
- Small, K. A. (1983). 'The incidence of congestion tolls on urban highways'. In: *Journal of Urban Economics* 13.1, pp. 90–111. ISSN: 0094-1190. DOI: [http://dx.doi.org/10.1016/0094-1190\(83\)90047-5](http://dx.doi.org/10.1016/0094-1190(83)90047-5). URL: <http://www.sciencedirect.com/science/article/pii/0094119083900475>.
- Smith, T., Barrett, M., Parker, S. and Eoin, O. (2011). *Description of GloTraM-2, a prototype model to calculate the future energy emissions and costs of the global shipping industry*. Tech. rep.
- Stochniol, A. (2012). 'A rebate mechanism for an equitable maritime emission reduction scheme'. In: *Maritime transport and the climate change challenge*. Routledge, p. 112.
- Tabuchi, T. and Thisse, J.-F. (2006). 'REGIONAL SPECIALIZATION, URBAN HIERARCHY, AND COMMUTING COSTS*'. In: *International Economic Review* 47.4, pp. 1295–1317. ISSN: 1468-2354. DOI: 10.1111/j.1468-2354.2006.00414.x. URL: <http://dx.doi.org/10.1111/j.1468-2354.2006.00414.x>.
- The Economist Intelligence Unit (2008). *Fuelling global trade - How GDP growth and oil prices affect international trade flows*. Report. The Economist Intelligence Unit Limited. URL: http://graphics.eiu.com/upload/DHL_Nov_main_Nov28_Final.pdf.
- Theil, H. (1969). 'A Multinomial Extension of the Linear Logit Model'. English. In: *International Economic Review* 10.3, pp. 251–259. ISSN: 00206598. URL: <http://www.jstor.org/stable/2525642>.
- Timothy, D. J. and Butler, R. W. (1995). 'Cross-border shopping'. In: *Annals of Tourism Research* 22.1, pp. 16–34. ISSN: 0160-7383. DOI: [http://dx.doi.org/10.1016/0160-7383\(94\)00052-T](http://dx.doi.org/10.1016/0160-7383(94)00052-T). URL: <http://www.sciencedirect.com/science/article/pii/016073839400052T>.

- Tinbergen, J. (1962). *Shaping the World Economy; Suggestions for an International Economic Policy*. T. URL: <http://hdl.handle.net/1765/16826>.
- Tolofari, S. R., Button, K. J. and Pitfield, D. E. (1986). 'Shipping Costs and the Controversy Over Open Registry'. In: *The Journal of Industrial Economics* 34.4, pp. 409–427. ISSN: 00221821, 14676451. URL: <http://www.jstor.org/stable/2098626>.
- Train, K. E. (2009). *Discrete choice methods with simulation*. Cambridge University Press.
- Trefler, D. (1995). 'The Case of the Missing Trade and Other Mysteries'. English. In: *The American Economic Review* 85.5, pp. 1029–1046. ISSN: 00028282. URL: <http://www.jstor.org/stable/2950973>.
- Truong, T. P. and Hensher, D. A. (1985). 'Measurement of Travel Time Values and Opportunity Cost from a Discrete-Choice Model'. English. In: *The Economic Journal* 95.378, pp. 438–451. ISSN: 00130133. URL: <http://www.jstor.org/stable/2233219>.
- UN (2015). *United Nations Sustainable Development Goals*. URL: <http://www.un.org/sustainabledevelopment/sustainable-development-goals/>.
- UNCTAD (2014). *Review of maritime transport*. Report. URL: http://unctad.org/en/PublicationsLibrary/rmt2014_en.pdf.
- UNFCCC (1998). *The Kyoto Protocol*. URL: <http://unfccc.int/resource/docs/convkp/kpeng.pdf>.
- (2012). *Emissions from fuel used for international aviation and maritime transport (international bunker fuels)*. URL: http://unfccc.int/methods_and_science/emissions_from_intl_transport/items/1057.php (visited on 11/12/2012).
- (2015). *The Paris Agreement*. URL: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf.
- UNWTO (2016). *Tourism Highlights 2016*. Report. World Tourism Organization. URL: <http://mkt.unwto.org/publication/unwto-tourism-highlights-2016-edition>.
- (2017). *World Tourism Organization - Who we are*. URL: <http://www2.unwto.org/content/who-we-are-0>.
- UPS (2016). *U.S. air cargo export rates*. URL: <https://www.ups.com/aircargo/using/rates/rates-zonechart.html> (visited on 17/07/2016).
- U.S. Department of Transportation (2014). *Bureau of Transportation Statistics, TranStats*. URL: <http://www.transtats.bts.gov>.
- U.S. Travel Association (2015). *U.S. Travel and Tourism Overview*. URL: https://www.ustravel.org/system/files/Media%20Root/Document/Travel_Economic_Impact_Overview.pdf.
- Vanat, L. (2016). *International report on snow and mountain tourism*. Tech. rep. URL: <http://www.vanat.ch/RM-world-report-2016-vanat.pdf>.
- Verleger, P. K. (1972). 'Models of the Demand for Air Transportation'. In: *The Bell Journal of Economics and Management Science* 3.2, pp. 437–457. ISSN: 00058556. URL: <http://www.jstor.org/stable/3003032>.
- Vivid Economics (2010). *Assessment of the economic impact of market-based measures, prepared for the Expert Group on Market-based Measures, International Maritime Organ-*

- ization. Report. Vivid Economics. URL: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Documents/VividEconomicsIMOFinalReport.pdf>.
- Vranes, E. (2009). *Trade and the Environment: Fundamental Issues in International Law, WTO Law, and Legal Theory*. Oxford Scholarship Online. DOI: 10.1093/acprof:oso/9780199562787.001.00.
- Walmsley, T., Aguiar, A. and Narayanan, B. (2012). *Introduction to the Global Trade Analysis Project and the GTAP Data Base*. Tech. rep.
- WEF (2015). *The travel & tourism competitiveness report 2015*. Tech. rep. The World Economic Forum. URL: http://www.weforum.org/docs/TT15/WEF_Global_Travel&Tourism_Report_2015.pdf.
- Williams, H. C. W. L. (1977). 'On the Formation of Travel Demand Models and Economic Evaluation Measures of User Benefit'. In: *Environment and Planning A* 9.3, pp. 285–344. DOI: 10.1068/a090285. eprint: <http://epn.sagepub.com/content/9/3/285.full.pdf+html>. URL: <http://epn.sagepub.com/content/9/3/285.abstract>.
- World Bank (2011). *Mobilizing Climate Finance*. Report. World Bank. URL: <https://www.imf.org/external/np/g20/pdf/110411c.pdf>.
- (2015). *World Bank Group Forum Highlights the Economic Power of Tourism*. URL: <http://www.worldbank.org/en/news/feature/2015/12/11/world-bank-group-forum-highlights-the-economic-power-of-tourism>.
- (2016). *World Integrated Trade Solution (WITS)*. URL: <http://wits.worldbank.org/>.
- (2017). *World Bank Open Data*. URL: <http://data.worldbank.org/>.
- World Travel and Tourism Council (2015). *Economic impact analysis*. URL: <http://www.wttc.org/research/economic-research/economic-impact-analysis/country-reports/>.
- Wright, R. (2010). 'World's fastest container ships mothballed.' In: *Financial Times* February 22. URL: <https://www.ft.com/content/65e522dc-1fce-11df-8deb-00144feab49a>.
- WTO (1947). *The General Agreement on Tariffs and Trade*. Tech. rep. URL: https://www.wto.org/english/docs_e/legal_e/gatt47_01_e.htm.
- (2013). *World Trade Report 2013 - Factors shaping the future of world trade*. URL: http://www.wto.org/english/res_e/booksp_e/world_trade_report13_e.pdf (visited on 18/08/2014).
- (2014). *The World Trade Organization - International trade and market access data*. URL: http://www.wto.org/english/res_e/statis_e/statis_e.htm (visited on 20/08/2014).
- (2016). *Tourism sector highlighted as important contributor to trade and development*. URL: https://www.wto.org/english/news_e/news16_e/bus_13jul16_e.htm (visited on 01/05/2017).
- Yeaple, S. R. (2003). 'The complex integration strategies of multinationals and cross country dependencies in the structure of foreign direct investment'. In: *Journal of Interna-*

- tional Economics* 60.2, pp. 293–314. ISSN: 0022-1996. DOI: [http://doi.org/10.1016/S0022-1996\(02\)00051-X](http://doi.org/10.1016/S0022-1996(02)00051-X). URL: <http://www.sciencedirect.com/science/article/pii/S002219960200051X>.
- Yi, K.-M. (2003). ‘Can Vertical Specialization Explain the Growth of World Trade?’ In: *Journal of Political Economy* 111.1, pp. 52–102. ISSN: 00223808, 1537534X. URL: <http://www.jstor.org/stable/10.1086/344805>.
- Zhu, S., Yamano, N. and Cimper, A. (2011). *Compilation of bilateral trade database by industry and end-use category*. Working Paper. DOI: 10.1787/5k9h6vx2z07f-en.

Appendix A

Appendix to Chapter 4

A.1 Data appendix

Mode-specific trade data from Eurostat. Eurostat publishes International Trade in Goods Statistics (ITGS) through different datasets (Eurostat, 2014). ITGS is grouped into extra-EU and intra-EU trade. Extra-EU trade includes international trade of EU member states with non-EU member states. Intra-EU trade includes international trade between EU member states only.

EU-extra trade is reported by mode of transport¹ since the year 2000 with a statistical threshold of 1,000€ and 1,000kg. For intra-EU trade, the collection of mode of transport has been optional for Member States since 2001, and as a consequence, only some countries provide these data wholly or partially. No trade data by mode of transport is therefore made available by Eurostat for intra-EU trade.

The trade value corresponds to the statistical value that is declared on the customs declaration form by businesses and private individuals involved in an international transaction of goods. The statistical value is 'the amount that would be invoiced in the event of sale or purchase at the national border of the reporting country' (Eurostat, 2014). For exports, this value is said to be a FOB (free on board) valuation, for imports a CIF (cost, insurance, freight) valuation. For imports, the statistical value includes transport and insurances costs incurred on the part of the journey located *outside the territory* of the importing country. For exports, the statistical value includes transport and insurances costs on the part of the journey located *on the territory* of the exporting country (Eurostat, 2014). Assuming that "domestic" transport and insurance costs are small in comparison to the overall goods value, the FOB trade value is usually also referred to as the production value at the factory gate. Import values should therefore be higher than the mirror export values as

¹Supplement 3 of the ComExt intra- and extra-European trade database in Eurostat (2015).

they include trade costs. Statistical values do not include taxes in import or export (e.g. customs and excise duties or VAT).

Bilateral trade quantities are reported in kilograms of the goods' net mass (i.e. the mass without packaging) and for certain goods, a supplementary quantity information is available (e.g. litres, number of pieces, carats, terajoules or square meters).

The standard product classification for the trade in goods by mode of transport by Eurostat is the 'Nomenclature uniforme des marchandises pour les Statistiques de Transport, Révisée', abbreviated NST/R. I group the data by NST/R into the economic sectors of energy production, mining and quarrying, agriculture and forestry, and manufacturing. Each economic sector is further divided into industries, which I specify according to the NACE Statistical Classification of Economic Activities. No conversation tables exist between NACE and NST/R trade, as the former refers to economic activities and the latter to international trade. The conversation table I used for aggregation is shown in Appendix D.

The country classification of extra-EU trade data follows the 'Nomenclature of countries and territories for the external trade statistics of the Community and statistics of trade between Member States' or in short 'Geonomenclature'.

The mode of transport is defined as the *active means of transport* by which goods are either presumed to leave (exports) or to have entered (imports) the statistical territory of the Community. The active means of transport is the means of transport providing the motive power. In the case of several means of transport, the active means of transport is identified as the one providing the motive power for the whole combination (Pongas, 2006). The modes of transport considered in extra-EU trade are: air, fixed installation (including pipelines), inland waterways, post, rail, road, sea, self propulsion and unknown.

For some observations, the reported active means of transport is different from the expected primary mode of transport. By *primary mode of transport*, I refer to the mode of transport which is used to bridge the greatest distance between the origin and destination country. The primary mode of transport is therefore the relevant mode of transport to calculate bilateral transport costs.

The expected primary mode of transport can be verified by surveying the data for countries sharing the same landmass (relevant for road rail and inland water transport, e.g. EU imports from the US by road are implausible). My analysis suggests that a significant number of trade flows by road, rail and inland water transport are incorrectly reported. For these observations I manually adjust the mode of transport and assume sea transport to be the default mode. I choose sea transport rather than air transport as it is unlikely that goods, which arrive via air in a non-EU country, are loaded onto "slower" means of transport (i.e. inland water, road, rail) for their international onward journey (thereby

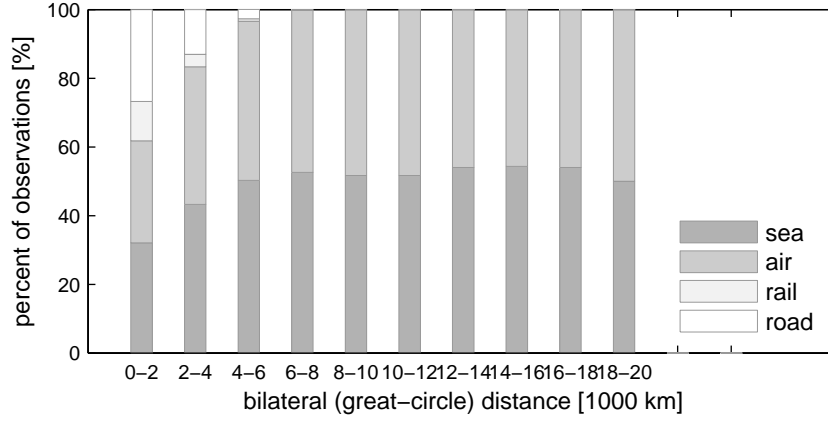


Figure A.1: Number of observations by mode of transport.

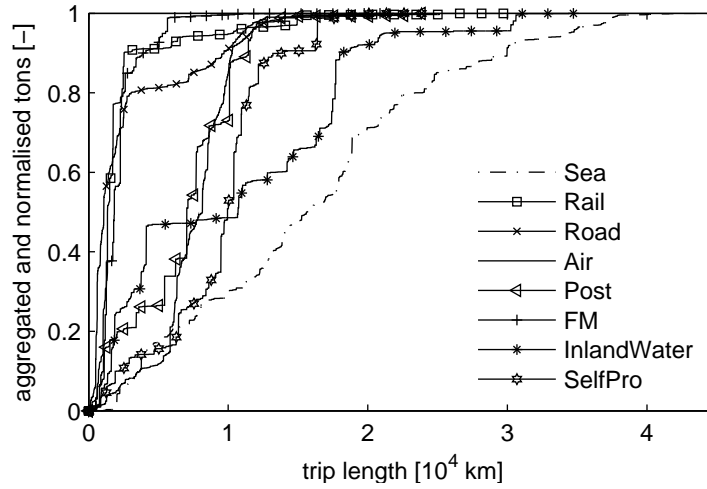


Figure A.2: Cumulative tonnage breakdown by mode of transport (active means of transport) as a function of trip length for *unadjusted* EU imports between 2001-13. FM = fixed mechanism, SelfPro = Self propulsion.

crossing the statistical territory of the EU). The final dataset does not contain any trade by road or rail between countries further than 6,000km apart as shown in Figure A.1.

Figure A.2 shows the cumulative distribution function for different transport modes of *unadjusted* extra-EU trade. Trade that moves via air (measured in tonnes) becomes significant only at a distance of 6,000km. This might however primarily be due to the missing flows of intra-EU trade. In comparison, trade by sea seems to be utilised irrespective of how far or how close the importer might be (indicated by the almost constant slope). Intuitively, the majority of trade by road and rail moves only very short distance, i.e. less than 3,000km. Trade by road, rail and inland water beyond 3,000km however may refer to the (reported) active means of transport rather than the primary means of transport as described above.

Table A.1 gives an overview of trade data by mode of transport and industry from Eurostat. Energy commodities, such as crude petroleum, gaseous hydrocarbons and coal, represent

60% and thus the primary share of commodities traded by weight followed by iron ore and minor bulk² with 11% (column 3). These commodities are transported on large vessels to utilise economies of scale. In contrast, the highest share of commodities traded by value is among manufactured goods³ (70%), including machinery and vehicles (16%), electronic and electrical equipment (13%), and wearing apparel and leather (with 7% of total trade by value, column 4). The transport of manufactured goods is accomplished by a range of different transport modes (columns 5 to 10), with sea transport being the dominant mode of transport by weight for all industries (column 5), followed by road (column 7) and rail transport (column 6). A significant amount of oil and gas enters the EU also via pipelines (column 9). Air transport remains insignificant (with a total share of 0.2% by weight) except for wearing apparel and electronics. If measured by value however, air transport obtains a 15% share among all other transport modes utilised (column 11). The high share of non-ferrous ores and concentrates transported via air might be a result of rare earth elements trade with relatively high unit values. As expected, containerisation is significant for fruits and vegetables and for all manufactured goods (column 12). Column 13 reports the median and upper and lower quantile of the value-to-weight ratio in €/kg which are significantly higher for manufactured goods. It is also apparent that for goods with higher unit values, the heterogeneity in value-to-weight increases. The commodities live animals, gold, coins and medals stand out in terms of their value-to-weight ratio and air transport share.

Maritime transport cost and trade data from the OECD. The OECD Maritime Transport Cost database (OECD, 2007) contains trade values (CIF and FOB) as well as transport costs of seaborne trade between 1991 and 2007. The data is available for 43 importing countries (including EU-15 countries as a custom union) from 218 countries of origin at 6 digit commodity level of the Harmonized System and 4 transport modes. The database is restricted to international trade by sea. The data was collected by the Trade and Agriculture Directorate from the statistical authorities of the United States, Australia, New Zealand and Latin America (foremost Argentina and Brazil however). Missing values were estimated using shipping freight rates data from a range of different sources including UNCTAD, Containerisation International, Drewry Shipping Consultants, International Grains Council, and the Baltic Exchange (Korinek, 2011). The four transport modes refer to clean/dry bulk carriers, dirty bulk carriers, tankers, and containers. Similar to above, I group the data into the economic sectors and NACE industries. The conversation table I used for aggregation is shown in Appendix D.

Table A.2 gives an overview of MTC trade data by mode of transport and industry. On

²As in UNCTAD (2014) I consider coal, iron ore and grain as major bulk but group other ores and concentrates (incl. bauxite and aluminium), phosphates, sand, salt, chalk, pumice stones and natural fertilisers into minor bulk.

³Due to the a large amount of crude petroleum imports by weight, the respective value in € still remains to be the largest observed although the value-to-weight ratio is lowest.

average, the transport of manufactured goods accounts for 5% of the traded value. This value translates into a 0.19\$/kg freight rate in 2007. For comparison, Anderson and Wincoop (2004) report 10.7% as their preferred estimate of the ad valorem tax equivalent of bilateral transport costs. The discrepancy between both values is expected and depends on the level of disaggregation as illustrated in Table A.2. For the 16 different subgroups of seaborne manufacturing trade, I obtain average values between 4% and 11%.

For the total of manufacturing imports, the value to weight ratio ranges from 0.95 to 4.71\$/kg, ad valorem transport costs range from 3 and 8%, and freight rates range from 0.12 to 0.31\$/kg. For the non-manufacturing commodities iron ore, coal and minor bulk, I obtain an ad valorem tax equivalent above 20%, although freight rates are as low as 0.04-0.06\$/kg. This is because of a relatively low unit value of these commodities ranging between 0.14 and 0.44\$/kg. Lastly, Table A.2 also indicates that transport in tankers is cheapest, followed by bulk carriers and then container ships. Container freight rates are higher, primarily because of higher average sea speeds (IMO, 2014) and thus fuel burn but also because of higher average cargo handling and port costs.

Table A.1: Descriptive statistics by industry and mode of transport of extra-EU imports in 2013. Data from Eurostat (2014). The last column shows median values, with the 25% quartile and 75% quartile in brackets.

(1) #	(2) Economic sector and industry	(3) Quantity 1000 tonnes	(4) Value Million €	(5) Sea %w	(6) Rail %w	(7) Road %w	(8) Air %w	(9) FM %w	(10) Un- known %w	(11) Air by value %v	(12) Container- isation %w	(13) Value to weight ratio €/kg
Energy production												
1	Crude petroleum	496,705 (35%)	301,647 (21%)	82	0	0	0	14	4	0	0	.61 (.58-.643)
2	Gaseous hydrocarbons	134,340 (10%)	57,823 (04%)	41	2	0	0	57	0	0	0	.64 (.54-.921)
3	Coal, lignite & peat (major bulk)	192,845 (14%)	15,853 (01%)	90	5	0	0	0	4	0	1	.10 (.08-.170)
Mining and quarrying												
4	Iron ore (major bulk)	92,506 (07%)	8,610 (01%)	73	22	0	0	0	4	0	2	.10 (.08-.146)
5	Minor bulk	51,215 (04%)	29,198 (02%)	80	8	8	0	2	0	43	4	1.0 (.28-7.53)
Agriculture and forestry												
6	Grain (major bulk)	17,078 (01%)	4,780 (00%)	94	3	1	0	0	0	1	8	.7 (.37-1.48)
7	Fruits and vegetables	14,090 (01%)	15,661 (01%)	74	0	20	2	0	3	6	37	1.8 (.88-4.22)
8	Wood and cork	27,175 (02%)	4,668 (00%)	38	32	28	0	0	0	0	7	.8 (.38-1.40)
Manufacturing												
9	Food products	34,028 (02%)	61,875 (04%)	75	1	13	1	0	10	2	34	2.5 (1.5-5.33)
10	Beverages	3,260 (00%)	4,921 (00%)	59	4	22	0	8	8	1	50	2.2 (1.0-5.00)
11	Tobacco products	15 (00%)	255 (00%)	51	0	30	8	0	10	23	35	12.5 (6.0-37.0)
12	Textiles	5,064 (00%)	21,744 (01%)	79	0	17	2	0	1	8	70	7.0 (3.4-17.6)
13	Wearing apparel & leather	7,764 (01%)	97,957 (07%)	67	0	14	7	0	12	14	56	21.0 (12-36.6)
14	Wood and cork products	7,699 (01%)	4,652 (00%)	46	17	34	0	0	2	1	23	2.3 (1.0-6.00)
15	Paper	15,671 (01%)	14,630 (01%)	79	1	16	0	0	3	7	26	4.5 (1.5-12.0)
16	Refined petroleum products	136,488 (10%)	85,345 (06%)	86	2	1	0	1	8	0	2	.9 (.68-3.56)
17	Chemicals	50,723 (04%)	76,346 (05%)	76	10	8	0	0	5	18	15	2.5 (1.0-17.7)
18	Pharmaceutical	1,644 (00%)	56,190 (04%)	59	1	32	4	0	4	36	51	18.5 (5.5-66.1)
19	Rubber and plastic	12,645 (01%)	30,662 (02%)	77	1	18	1	0	4	9	55	3.7 (1.8-10.4)
20	Non-metallic mineral products	28,235 (02%)	16,231 (01%)	84	3	11	0	0	1	38	27	2.2 (.64-11.0)
21	Basic metals and metal products	50,929 (04%)	86,622 (06%)	73	9	12	0	0	5	10	20	4.3 (1.7-16.0)
22	Electronic & electrical equipment	8,219 (01%)	184,199 (13%)	70	1	18	6	0	5	47	59	31.8 (9.6-95.5)
23	Machinery & vehicles	18,956 (01%)	238,847 (16%)	61	1	16	3	0	12	28	40	13.3 (5.7-46.0)
24	Furniture	4,055 (00%)	12,985 (01%)	84	0	12	0	0	3	5	78	4.5 (2.5-10.5)
Other												
25	Live animals	6 (00%)	202 (00%)	7	0	52	39	0	1	89	2	14.9 (7.0-41.8)
26	Gold, coins & medals	3 (00%)	19,947 (01%)	41	0	23	35	0	0	71	46	1490 (15-18526)

Table A.2: Descriptive statistics of unit and ad valorem transport costs by industry in seaborne trade in 2007. Data from OECD (2007). Reported is the median, with the 25% quartile and 75% quartile in brackets. Ad valorem values are calculated by dividing transport costs by the CIF trade value.

(1) #	(2) Economic sector and industry	(3) Container freight rate 2007\$/kg	(4) ad valorem %	(5) Bulk: dirty/industrial or <i>clean/dry</i> freight rate 2007\$/kg	(6) ad valorem %	(7) Tanker freight rate 2007\$/kg	(8) ad valorem %	(9) Value to weight ratio 2007\$/kg
Energy production								
1	Crude petroleum	-	-	-	-	0.01 (0.01-0.02)	3 (2-4)	0.50 (0.40-0.67)
2	Gaseous hydrocarbons	-	-	0.54 (0.00-1.08)	2 (1-3)	0.10 (0.04-0.18)	8 (5-13)	0.75 (0.63-2.46)
3	Coal, lignite & peat (major bulk)	0.14 (0.09-0.25)	18 (9-27)	0.06 (0.02-0.12)	21 (12-33)	-	-	0.44 (0.22-1.05)
Mining and quarrying								
4	Iron ore (major bulk)	-	-	0.04 (0.02-0.09)	26 (15-36)	-	-	0.14 (0.07-0.37)
5	Minor bulk	-	-	0.06 (0.03-0.11)	20 (10-30)	-	-	0.35 (0.14-0.76)
Agriculture and forestry								
7	Grain (major bulk)	-	-	0.08 (0.05-0.14)	12 (7-19)	-	-	0.74 (0.34-1.42)
8	Fruits and vegetables	0.16 (0.11-0.24)	9 (6-15)	-	-	-	-	1.70 (1.06-3.14)
6	Wood and cork	0.09 (0.03-0.21)	11 (5-17)	-	-	-	-	0.81 (0.33-1.97)
Manufacturing								
9	Food products	0.15 (0.11-0.23)	6 (4-9)	0.10 (0.07-0.14)	10 (6-13)	0.12 (0.07-0.20)	7 (5-10)	2.23 (1.22-3.64)
10	Beverages	0.12 (0.07-0.18)	7 (5-13)	-	-	-	-	1.50 (0.90-2.79)
11	Tobacco products	0.19 (0.13-0.30)	4 (2-7)	-	-	-	-	4.89 (2.98-9.98)
12	Textiles	0.27 (0.17-0.47)	6 (4-8)	-	-	-	-	5.06 (3.04-8.89)
13	Wearing apparel & leather	0.54 (0.34-0.93)	4 (2-6)	-	-	-	-	14.51 (8.88-26.08)
14	Wood and cork products	0.19 (0.10-0.42)	9 (5-14)	-	-	-	-	2.17 (1.16-4.89)
15	Paper	0.17 (0.09-0.33)	8 (5-12)	-	-	-	-	2.15 (1.06-4.37)
16	Refined petroleum products	-	-	0.10 (0.05-0.15)	9 (6-13)	0.05 (0.02-0.14)	5 (3-7)	1.00 (0.60-1.75)
17	Chemicals	0.19 (0.12-0.33)	5 (3-8)	0.09 (0.05-0.15)	8 (5-13)	-	-	2.50 (1.03-5.04)
18	Pharmaceutical	0.41 (0.25-0.74)	3 (2-5)	-	-	-	-	12.99 (6.71-24.42)
19	Rubber and plastic	0.19 (0.11-0.33)	6 (4-8)	-	-	-	-	3.02 (2.01-5.10)
20	Non-metallic mineral products	0.17 (0.10-0.38)	10 (6-16)	-	-	-	-	1.96 (0.85-4.84)
21	Basic metals and metal products	0.19 (0.11-0.34)	5 (3-7)	0.08 (0.06-0.11)	7 (5-10)	-	-	2.85 (1.32-5.85)
22	Electronic & electrical equipment	0.39 (0.24-0.64)	4 (2-6)	-	-	-	-	11.73 (6.98-19.26)
23	Machinery & vehicles	0.37 (0.23-0.57)	4 (2-7)	-	-	-	-	9.05 (5.52-15.53)
24	Furniture	0.44 (0.26-0.72)	9 (6-14)	-	-	-	-	4.78 (2.96-8.46)
27	Total Manufacturing	0.19 (0.12-0.31)	5 (3-8)	0.08 (0.05-0.13)	9 (5-13)	0.07 (0.03-0.15)	6 (3-8)	2.26 (0.95-4.71)
Other								
25	Live animals	0.45 (0.39-1.46)	9 (7-14)	-	-	-	-	5.93 (3.43-23.66)
26	Gold, coins & medals	0.57 (0.34-1.00)	5 (3-9)	-	-	-	-	13.31 (6.69-26.42)

Cells with no observations indicated by "-".

A.2 Estimation of transit time

Bilateral transit time is modelled as a function of average distance and average transport speed. Because vehicles encounter different operational segments between the points of origin and destination, the average transport speed over the entire journey is lower than the vehicle's optimum design speed. For example, trucks first need to leave the city on narrow roads before going on a highway; after take-off, aircraft first need to go through different climb segments before they reach the cruise altitude and hence cruise speed. Taking all those effects together and dividing the time lost by the time which would be needed if the entire distance had been travelled at maximum cruising speed provides a measure of time inefficiencies with respect to average distances travelled. Holding the time lost by inefficiencies constant, this ratio decreases with increasing distance as the inefficiencies become less prominent in the overall journey time. The speed-distance relationship $v(D)$ is best described by a power function of the form $v = \beta_0 D^{\beta_1}$ (Schäfer, 2015). This function can be fitted using data on average cruising speeds and average trip distances and provides the baseline for complementing the extra-EU trade data with average mode-specific transit times.

To be able to additionally control for maximum cruising speeds—e.g. the drag divergence Mach number for aircraft (a physical constraint) or speed limits on highways (a practical constraint)—the shape of the fitted functional form has to be skewed to either the left or the right hand side (along the x -axis), while the position along the y -axis has to be corrected via an additional constant

$$v = \beta_2 + \beta_0 (D + \beta_3)^{-\beta_1}. \quad (\text{A.1})$$

Assuming that the maximum transport speed is reached if distance D approaches infinity

$$\lim_{D \rightarrow \infty} v(D) = \beta_2, \quad \forall \beta_1 > 1 \quad (\text{A.2})$$

yields $\beta_2 = v_{\max}$. This curve is then further constrained to pass through the zero-point. It follows that $\beta_2 = -\beta_0 (\beta_3)^{-\beta_1}$ and hence $\beta_0 = -v_{\max} \beta_3^{\beta_1}$. Equation A.1 is thus specified to account for inefficiencies that occur on shorter distances D by reducing the maximum cruising speed by the amount $\beta_0 (D + \beta_3)^{-\beta_1}$. Substituting β_2 and β_0 in Equation A.1 yields

$$v = v_{\max} \left[1 - \left(\frac{\beta_3}{D + \beta_3} \right)^{\beta_1} \right], \quad (\text{A.3})$$

which I estimate using nonlinear least squares.

For subsonic aircraft, the cruise speed is limited by the drag divergence Mach number,

which converts to a maximum cruise speed of approximately 486kts⁴. Observations with a speed value above the maximum are identified as outliers. Figure A.3 shows the data and the fitted curve.

For container ships (only trade in manufacturing goods is considered), the curve is fitted using data from IMO (2014), which has been extracted using a method developed by Prakash (forthcoming). For ships, the theoretical maximum hull speed is a function of the Froude number. I therefore estimate the average maximum hull speed by choosing a value of v_{\max} such that $\beta_1 \approx 1$. Figure A.4 shows the data and the fitted curve.

The transport between countries is assumed to be direct, i.e. without intermediate stops or a diversion from the most optimum route. For sea transport, I use trade weighted bilateral sea distances from Newton (2009). For air transport, I use great circle distances which I calculate between economic centres⁵ with latitude and longitude coordinates data taken from Mayer and Zignago (2011).

Bilateral mode specific international distances are then used to calculate average mode specific air and sea speed before converting them into the average bilateral transit time by transport mode between countries.

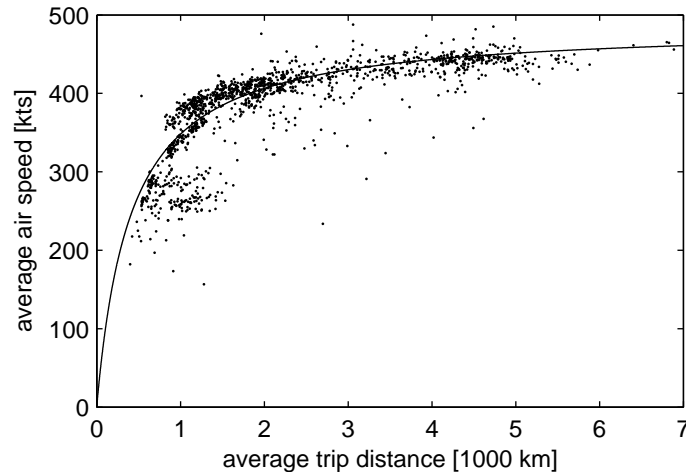


Figure A.3: Air speed as a function of average trip distance of U.S. air freight carriers between 1990 and 2013 by airline and by quarter. Data taken from the U.S. Department of Transportation (2014). Fitted functional form using avg. distance in [km] to obtain avg. speed in [kts]: $v_{\max} = 486\text{kts}$, $\beta_1 = 1.03$, and $\beta_3 = 417.35$.

⁴Depending on the cost of fuel, the cruising speed is either at or slightly below the drag divergence Mach number (Kroo and Shevell, 2001). Typical cruising Mach numbers of new generation passenger aircraft (such as the Boeing B787 or the Airbus A350) are in the range of Mach 0.85. At a typical cruising altitude of 35,000ft, this value converts to approximately 486kts.

⁵The main city represents the country's economic centre (measured by population density), which is in almost all cases also the capital of the respective country.

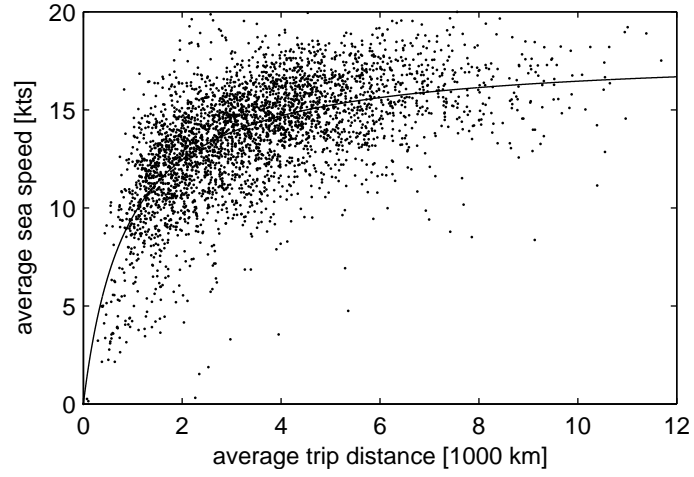


Figure A.4: Sea speed as a function of average trip distance of container ships in 2013. Data from IMO (2014), extracted using the method by Prakash (forthcoming) and aggregated by IMO ship number. Fitted functional form using avg. distance in [km] to obtain avg. speed in [kts]: $v_{\max} = 17.9\text{kts}$, $\beta_1 = 1.00$, and $\beta_3 = 871.84$.

A.3 Additional figures

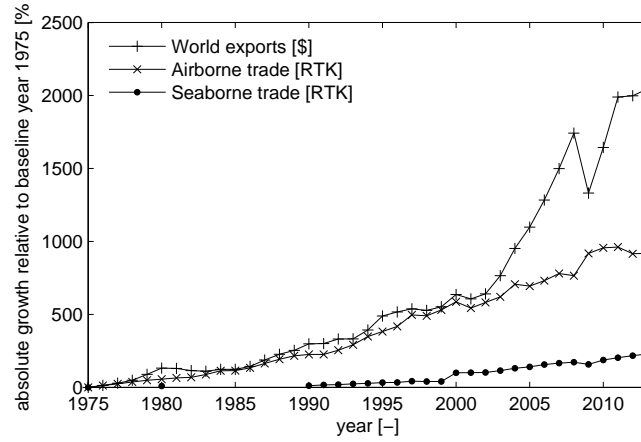


Figure A.5: Growth in airborne vs. seaborne trade, measured in revenue tonne-kilometres (RTK). The growth in world merchandise exports is shown for reference. Data from the World Bank (2017) (air), UNCTAD (2014) (sea) and WTO (2014).

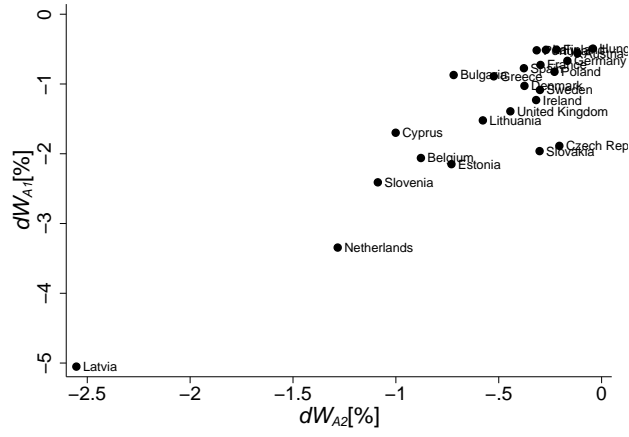


Figure A.6: Differences in calculated welfare changes of policy A using options 1 and 2.

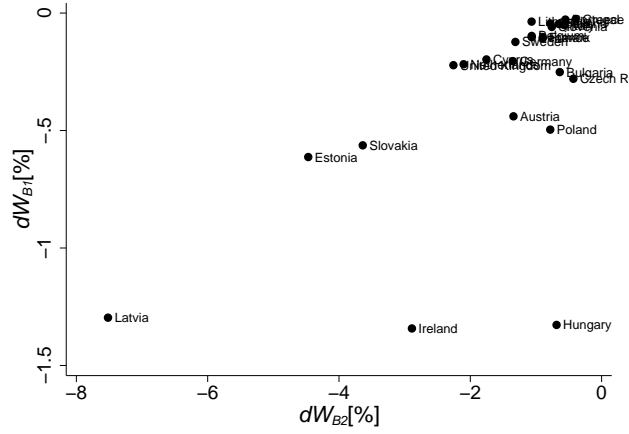


Figure A.7: Differences in calculated welfare changes of policy B using options 1 and 2.

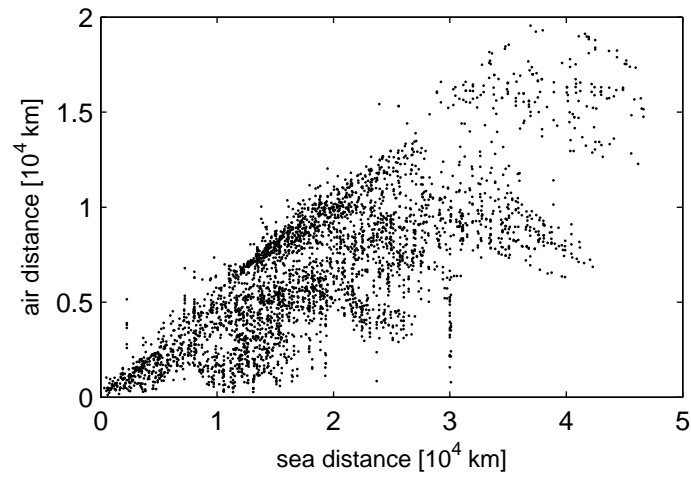


Figure A.8: Sea vs. air distance of manufactured goods imported into the EU. Sea distances are trade weighted by port of origin and destination and taken from Newton (2009); air distances are calculated great-circle distances between countries' economic centres.

Appendix B

Appendix to Chapter 5

B.1 Mathematical appendix

PROOF OF PROPOSITION 1

Step 1. Changes in the price index

The price index of consumers in the tourism sector P_j is given by the CES exact price index in Equation 5.10. To quantify changes in P_j , the price parameter $\Phi_j \equiv \sum_{i=1}^I S_i (A_i a_{ji})^\theta p_{ji}^{-\theta}$ can be combined with the CES exact price index given by $P_j \equiv \gamma \Phi_j^{-1/\theta}$ to obtain

$$(P_j)^{-\theta} = \gamma^{-\theta} \Phi_j = \gamma^{-\theta} \sum_{i=1}^I S_i (A_i a_{ji})^\theta p_{ji}^{-\theta}$$

Noting that γ is a constant and that S_i , A_i and a_{ji} remain constant by R2, small changes in the price index satisfy

$$\begin{aligned} d \ln P_j &= \sum_{i=1}^I \lambda_{ji} d \ln p_{ji} \\ &= \sum_{i=1}^I \lambda_{ji} (d \ln w_i + d \ln \tau_{ji}). \end{aligned} \tag{B.1}$$

Recalling that gravity can be written as $\frac{X_{ji}}{X_j} = \lambda_{ji} = P_j^\theta S_i A_i^\theta w_i^{-\theta} a_{ji}^\theta \tau_{ji}^{-\theta}$, with domestic flows given by $\frac{X_{jj}}{X_j} = \lambda_{jj} = P_j^\theta S_j A_j^\theta w_j^{-\theta} a_{jj}^\theta \tau_{jj}^{-\theta}$, the odds ratio can be specified as

$$\frac{\lambda_{ji}}{\lambda_{jj}} = \frac{S_i}{S_j} \left(\frac{A_i a_{ji}}{A_j a_{jj}} \right)^\theta \left(\frac{w_i \tau_{ji}}{w_j \tau_{jj}} \right)^{-\theta},$$

where the price index P_j cancels out. Taking the derivative of this expression reveals

$$d \ln \lambda_{ji} - d \ln \lambda_{jj} = \epsilon (d \ln w_i + d \ln \tau_{ji} - d \ln w_j), \quad (\text{B.2})$$

where $\epsilon \equiv -\theta$, $\tau_{jj} \equiv 1$, and \mathbf{S} , \mathbf{A} , and \mathbf{a} remain constant by R2. It should be noted that the same expression could be obtained if the definition of the demand elasticity in Equation 5.21 was used instead: $\epsilon \equiv -\theta = \frac{\partial \ln (X_{ji}/X_{jj})}{\partial \ln p_{ji}} = \frac{\partial \ln (\lambda_{ji}/\lambda_{jj})}{\partial \ln p_{ji}}$.

Combining Equations B.1 and B.2 yields

$$\begin{aligned} d \ln P_j &= \sum_{i=1}^I \lambda_{ji} \left(\frac{d \ln \lambda_{ji} - d \ln \lambda_{jj}}{\epsilon} + d \ln w_j \right) \\ &= \frac{\sum_{i=1}^I \lambda_{ji} (d \ln \lambda_{ji} - d \ln \lambda_{jj})}{\epsilon} + \sum_{i=1}^I \lambda_{ji} d \ln w_j \\ &= \frac{-d \ln \lambda_{jj}}{\epsilon} + d \ln w_j. \end{aligned}$$

Changes in the price index can then be obtained by integrating this expression between the initial equilibrium at time t (before the price shock) and the new equilibrium at time $t+1$ (after the price shock)

$$\hat{P}_j = \hat{w}_j \left(\hat{\lambda}_{jj} \right)^{-1/\epsilon}.$$

By equation 5.36, changes in real income are then given by

$$\begin{aligned} \hat{W}_j &= (\hat{w}_j)^{\gamma_j} \left(\hat{w}_j \left(\hat{\lambda}_{jj} \right)^{-1/\epsilon} \right)^{-\alpha_j} \\ &= (\hat{w}_j)^{\gamma_j - \alpha_j} \left(\hat{\lambda}_{jj} \right)^{\alpha_j/\epsilon}. \end{aligned} \quad (\text{B.3})$$

Step 2. Changes in income

Changes in income are determined from the market clearing condition and the changes in expenditure. Using the budget shares λ_{ij} given by Equation 5.19, and dividing them

by same equation that is written for the new equilibrium $\lambda'_{ji} = \frac{S_i A_i^\theta w_i'^{-\theta} a_{ji}^\theta \tau_{ji}'^{-\theta}}{\sum_{i=1}^I S_i A_i^\theta w_i'^{-\theta} a_{ji}^\theta \tau_{ji}'^{-\theta}}$ reveals

$$\hat{\lambda}_{ji} = \frac{(\hat{w}_i \hat{\tau}_{ji})^\epsilon}{\sum_{i'=1}^I \lambda'_{ji} (\hat{w}_i \hat{\tau}_{ji})^\epsilon}.$$

From the market clearing condition in Equation 5.13, a country's total income from the tourism sector in the new equilibrium is given by $Y_i' = \sum_{j'=1}^I X'_{ji} = \sum_{j'=1}^n \lambda'_{ji} X'_{j'}$. Because $\hat{v}v = v'$ for any variable v , this expression can be rewritten as $\hat{Y}_i Y_i = \sum_{j'=1}^I \hat{\lambda}_{ji} \lambda_{ji} \hat{X}_{j'} X_{j'}$, which in combination with the expression for changes in the budget shares from above

yields

$$\hat{Y}_i = \frac{1}{Y_i} \sum_{j=1}^I \frac{\lambda_{ji} (\hat{w}_i \hat{\tau}_{ji})^\epsilon}{\sum_{i'=1}^n \lambda'_{ji} (\hat{w}'_{i'} \hat{\tau}'_{ji})^\epsilon} \hat{X}_j X_j.$$

Because income from tourism is given by $Y_i = w_i L_i$ and using labour as the numeraire it follows that $\hat{Y}_i = \hat{w}_i$. In equal terms, using Equation 5.17, changes in total income are given by

$$\hat{Y}_j^E = (\hat{w}_j)^{\eta_j} = \hat{X}_j^E,$$

illustrating that changes in the total expenditure in the tourism sector (\hat{X}_j) are not equivalent to the changes in income of tourism workers (\hat{w}_j). This is because overall spending is determined by changes in both sectors: tourism and non-tourism.

One can link the overall changes in spending \hat{X}_j^E to the changes in spending in each sector \hat{X}_j by assuming that the percentage change in overall spending equivalently applies to all sectors of the economy

$$\hat{X}_j^E \equiv \hat{X}_j.$$

Under this assumption, a 1% reduction in overall spending would materialise into a 1% reduction in spending in the tourism sector as well as into a 1% reduction in spending in the non-tourism sector. This is therefore a reasonable approximation as in the aggregate, the 1% reduction in overall spending is retained.

Using these two observations in the expression from above, small changes in income satisfy

$$\hat{w}_i = \frac{1}{Y_i} \sum_{j=1}^I \frac{\lambda_{ji} (\hat{w}_i \hat{\tau}_{ji})^\epsilon}{\sum_{i'=1}^I \lambda'_{ji} (\hat{w}'_{i'} \hat{\tau}'_{ji})^\epsilon} (\hat{w}_j)^{\eta_j} X_j. \quad (\text{B.4})$$

Equation B.4 determines income in the tourism sector $w_i L_i$ as functions of the model parameters (ϵ) and of the prices and expenditure across countries. An implicit solution of Equation B.4 can be obtained by introducing foreign price shocks to any of the variables on the right hand side, and then solving for the vector of wages iteratively using a dampening factor (see e.g. Head and Mayer, 2014).

Step 3. Autarky

In autarky, all tourism activities are consumed domestically. The share of domestic tourism expenditure in the counterfactual equilibrium is therefore equivalent to one ($\lambda'_{jj} = 1$). The change in relative domestic tourism expenditure between the initial and the new equilibrium is then given by $\hat{\lambda}_{jj} = 1/\lambda_{jj}$. Applying these observations to Equation B.3,

changes in real income associated with moving to autarky can be calculated using

$$\widehat{W}_j^A = \left(\widehat{w}_j^A\right)^{\eta_j - \alpha_j^I} (\lambda_{jj})^{-\alpha_j/\epsilon}. \quad (\text{B.5})$$

The next step therefore requires to determine the changes in wages associated with moving to autarky \widehat{w}_j^A . The key insight of the size of \widehat{w}_j^A is given by the implicit solution of Equation B.4 above. In order to demonstrate, I proceed in three steps.

First, with $\epsilon < 0$, for all $i' = 1, \dots, j', \dots, n'$ the denominator of Equation B.4 becomes

$$\lim_{\tau' \rightarrow +\infty} \sum_{i'=1}^I \lambda'_{ji} \left(\widehat{w}_i' \widehat{\tau}_{ji}'\right)^\epsilon = 0 + \dots + \lambda'_{jj} \left(\widehat{w}_j' \widehat{\tau}_{jj}'\right)^\epsilon + \dots + 0,$$

as $\tau'_{jj} = \tau_{jj}$ by R2 and hence Equation B.4 provisionally reduces to

$$\widehat{w}_i^A = \frac{1}{Y_i} \sum_{j'=1}^I \frac{\lambda_{ji} \left(\widehat{w}_i \widehat{\tau}_{ji}^I\right)^\epsilon}{\lambda'_{jj} \left(\widehat{w}_j' \widehat{\tau}_{jj}'\right)^\epsilon} \left(\widehat{w}_j^A\right)^{\eta_j} X_j.$$

In the second step, the same methodology can be applied to the nominator of Equation B.4, now using the entire summation over j' . With $\epsilon < 0$, for all $j' = 1, \dots, i', \dots, n'$ the summation term of j' becomes

$$\lim_{\tau' \rightarrow +\infty} \sum_{j'=1}^I \frac{\lambda_{ji} \left(\widehat{w}_i \widehat{\tau}_{ji}^I\right)^\epsilon}{\lambda'_{jj} \left(\widehat{w}_j' \widehat{\tau}_{jj}'\right)^\epsilon} = 0 + \dots + \frac{\lambda'_{ii} \left(\widehat{w}_i \widehat{\tau}_{ii}'\right)^\epsilon}{\lambda'_{jj} \left(\widehat{w}_j' \widehat{\tau}_{jj}'\right)^\epsilon} + \dots + 0,$$

as $\tau'_{ii} = \tau_{ii}$ by R2 and hence

$$\widehat{w}_i^A = \frac{1}{Y_i} \frac{\lambda'_{ii} \left(\widehat{w}_i \widehat{\tau}_{ii}'\right)^\epsilon}{\lambda'_{jj} \left(\widehat{w}_j' \widehat{\tau}_{jj}'\right)^\epsilon} \left(\widehat{w}_j^A\right)^{\gamma_j} X_j.$$

Third, because in autarky $i = j$, it must be that $\lambda'_{ii} \left(\widehat{w}_i \widehat{\tau}_{ii}'\right)^\epsilon = \lambda'_{jj} \left(\widehat{w}_j' \widehat{\tau}_{jj}'\right)^\epsilon$, which thus gives

$$\begin{aligned} \widehat{w}_j^A &= \frac{X_j}{Y_j} \left(\widehat{w}_j^A\right)^{\gamma_j} \iff \\ \widehat{w}_j^A &= \left(\frac{X_j}{Y_j}\right)^{1/(1-\gamma_j)}. \end{aligned} \quad (\text{B.6})$$

Equations B.5 and B.6 can then be combined to reveal the result of Proposition 1.

B.2 Data appendix

Air travel itinerary data from Sabre. The global aviation Market Intelligence database of Sabre (2016) contains passenger traffic and sales data from bookings made via the three major global distribution systems Sabre, Amadeus and Travelport.

Origin and destination (O-D) passenger flows in the dataset refer to the total number of passengers travelling between any two countries, irrespective of how they got there in the first place (non-stop, connections, through flights, etc.). An individual passenger's journey is therefore reported as several O-D entries in the data. For example, a passenger travelling from Vienna (VIE) to New York (JFK) would show up in the **VIE-JFK-VIE** (outbound) as well as the **JFK-VIE-JFK** (inbound) itinerary. Using the filter option by point of origin country however, one can filter for inbound travel only. The *point of origin country* refers to the country where passengers started their journey. Using the example from above, the outbound journey is thus characterised by the itinerary **VIE-JFK-VIE** with VIE selected as the point of origin airport, whereas the inbound journey is characterised by the itinerary **JFK-VIE-JFK** with JFK selected as the point of origin airport.

In international tourism, passengers returning to their country of origin are however not classified as international tourists and need therefore be excluded from the total number of international tourist arrivals. This can be achieved by filtering the data for O-D flows, where the origin country is identical to the point of origin country. Inbound itineraries are therefore excluded. Using Austria as the origin country and the point of origin country, and the US as the destination country would include the number of passengers travelling from VIE to JFK on the **VIE-JFK-VIE** itinerary. The same criteria apply to connecting flights. For example, passengers travelling from Vienna to New York via London are included in the **VIE-LHR-JFK-LHR-VIE** itinerary using Austria as the point of origin country, but excluded from the **LHR-JFK-LHR** itinerary as the point of origin country should in this case only be the UK or the US.

By applying these filter criteria, the air travel itinerary data becomes a dataset that is representative for international tourism flows. Limitations however exist as the data does not contain passenger movements across borders using surface transport modes (e.g. rail and road). The total number of international tourist arrivals in the realised dataset is therefore smaller than the actual number of international tourist arrivals in each country. Table B.1 gives an overview.

The total number of international tourist arrivals for the top ten countries I obtain from the air travel itinerary data compare well to the numbers in UNWTO, 2016, considering that surface transport accounts for 46% (with road being 39%, rail 2% and water 5%) of global tourism movements (UNWTO, 2016). Significantly smaller numbers are obtained

for countries which are a popular destination for international tourism by road like France and the US. With air travel being the primary modes of transport for visits to the UK, the numbers should match more closely. Discrepancies however still exist due to differences in the reporting method. For example, the UNWTO data counts international tourists from numbers of overnight visitors. The data therefore indicates that there are a significant number of day trips into the UK, which is the reason for obtaining a higher number of international tourist arrivals using air travel itinerary data.

Table B.1: Top ten destination countries by international tourist arrivals (in millions)

Rank	All tourism acc. to UNWTO		Tourism via air transport using data from Sabre
	Country	2014 arrivals	2014 arrivals
1	France	83.7	22.9
2	USA	75.0	47.5
3	Spain	64.9	47.3
4	China	55.6	24.9
5	Italy	48.6	26.6
6	Turkey	39.8	19.6
7	Germany	33.0	26.5
8	United Kingdom	32.6	39.5
9	Mexico	29.3	12.4
10	Russian Federation	29.8	12.3

The Sabre data contains two types of airfares. The base airfare is the amount paid for the ticket for a one way trip and exclusive of any taxes. The total airfare is the base airfare plus taxes for a one way trip. Table B.2 gives an overview and shows that the amount of taxes paid (calculated as the difference between the two) is substantial. As these taxes are determined exogenously, they can be used as an instrument for the endogenously determined airfares in IV regression statistics. The amount paid for travel relative to the total amount paid for all tourism activities in the destination country (the ad valorem measure) is discussed in the main text. Transport costs in international tourism refer to the costs paid for return trips. O-D airfares (one way) need therefore be multiplied by two.

Table B.2: Unit and ad valorem air travel costs (return trips) in international tourism in 2014

Distance range [1000km]	Base airfare		Total airfare	
	airfare [2014\$]	ad valorem [%]	airfare [2014\$]	ad valorem [%]
0-1.0	216 (170-273)	26 (16-37)	341 (268-424)	42 (27-58)
1.0-2.5	279 (221-425)	31 (21-47)	443 (371-608)	49 (33-71)
2.5-5.0	645 (462-841)	55 (35-87)	894 (676-1,157)	78 (51-124)
5.0-7.5	873 (695-1,129)	76 (47-103)	1,274 (1,059-1,529)	111 (68-149)
7.5-10.0	994 (821-1,228)	79 (56-105)	1,451 (1,241-1,707)	116 (84-150)
10.0-15.0	1,385 (1,110-1,832)	92 (64-116)	1,888 (1,563-2,399)	126 (88-161)
15.0-20.0	1,799 (1,587-2,054)	87 (54-118)	2,385 (2,131-2,725)	120 (72-157)
Total	772 (416-1,125)	61 (34-96)	1,137 (605-1,570)	88 (52-136)

Notes: Descriptive statistics of unit and ad valorem air travel costs of international tourism in 2014. Data from Sabre (2016) and World Bank (2017). Base airfares are exclusive; total fares are inclusive of taxes, surcharges and other fees. Reported is the median value with the 25% quartile and 75% quartile reported in brackets. Ad valorem values are calculated by dividing airfares by the average price paid by tourists in the destination country (see Equation 5.22).

World Bank data. The World Bank (2017) provides tourism data by number of tourist arrivals and departures and tourism receipts and expenditures. The data is collected from the UNWTO and reported on an annual basis.

International inbound tourists refers to the total number of travellers entering a foreign country for any period less than 12 months and for any purpose other than a remunerated activity. The data is collected from statistical authorities from border statistics (police, immigration, and the like) or tourism statistics (tourism accommodation establishments) and may also include same-day visitors, cruise passengers, and crew members.

International tourism receipts (in current U.S. dollars) refer to balance of payments (BOP) expenditures by international inbound visitors (arrivals) and include payments for goods and services and payments to national carriers for international transport, both from overnight and same-day visitors. The BOP expenditures exclude expenditures from domestic tourists. The amount spent on activities is identified with the travel item of the BOP. The BOP estimates however also include expenditures associated with other types of travellers (e.g. long-term students or patients, border and seasonal workers).

International outbound tourists refers to the total number of travellers exiting their country of residence to any other country for any purpose other than a remunerated activity in the country visited.

International tourism expenditures (in current U.S. dollars) refer to the BOP expenditures of international outbound visitors in other countries from overnight and same-day visitors and include, for most of the countries, payments to foreign carriers for international transport.

WTTC data. *Domestic tourism expenditure.* The World Travel and Tourism Council (2015) uses the Tourism Satellite Account (TSA) method to measure the direct economic contribution of tourism consumption to a national economy (Frechtling, 2010). Data is collected from reports from individual country statistic and tourism bodies and includes spending for business and leisure trips. If these are not available, TSA data is used from the UNWTO. If TSAs are not available, domestic tourism receipts are estimated as a function of GDP and tourism expenditures.

Bilateral tourism variables.

Distance is the great circle distance in kilometres between the two major cities in each country. The major city is defined as the city with the highest population density. In the majority of cases, the major city is equivalent to the country's official capital. Data source: Mayer and Zignago (2011).

Direction of travel is an indicator variable if the preferred direction of travel is mainly

north to south as opposed to east-west, measured as the absolute difference in degrees of latitude between the country centroids of the origin and destination country, relative to the absolute difference in degrees of longitude between the country centroids. Latitude and longitude data is taken from the Portland State University Economics Department (2016).

Internet users refers to the lower average number of people using the internet in the origin and destination country as defined by Equation 5.32. An internet user is a person who has used the internet from any location and within the last 12 months via a computer, mobile phone, personal digital assistant, games machine, digital TV etc. Data source: World Bank (2017).

Tourism visa is a binary variable that equals one if bilateral visa restrictions are in place, and zero otherwise. Data source: Neumayer (2011)

Ski resort is a binary variable that equals one if both the origin and the destination country have at least one major ski resort, and zero otherwise. According to Vanat (2016), the 68 countries with a ski resort, representing 100% of the total inbound market volume, are: Austria, France, Italy, Liechtenstein, Switzerland, Andorra, Belgium, Denmark, Finland, Germany, Iceland, Norway, Portugal, Spain, Sweden, United Kingdom, Afghanistan, Albania, Armenia, Azerbaijan, Belarus, Bosnia & Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Greece, Hungary, Iran, Kazakhstan, Kosovo, Kyrgyzstan, Latvia, Lithuania, Macedonia, Montenegro, Pakistan, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Tajikistan, Turkey, Ukraine, Uzbekistan, Argentina, Canada, Chile, Mexico, United States, Australia, China, India, Japan, Mongolia, New Zealand, North Korea, South Korea, Algeria, Israel, Lebanon, Lesotho, Morocco, and South Africa.

Near coast is a binary variable that equals one if 54.3% of both countries' surface area is within 100 km of ice-free coast, and zero otherwise. 54.3% is the mean value of all countries in the data. Data source: Nunn and Puga (2012).

Common official language is a binary variable that equals one if both countries share the same official language, the same national language, or a language spoken by at least 20% of the population in either country, and zero otherwise. Data source: Mayer and Zignago (2011).

Colonial ties is a binary variable that equals one if the origin country ever colonised the destination country or vice versa after 1945, for a relatively long period of time and with a substantial participation in the governance of the colonized country, and zero otherwise. Data source: Mayer and Zignago (2011).

B.3 Additional results

Table B.3: Gains from international tourism (full list).

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Country	X_j/Y_j	λ_{jj}	α_j	γ_j	$\widehat{W}_{j,w}$	$\widehat{W}_{j,\lambda_{jj}}$	\widehat{W}_j
		[-]	[%]	[%]	[%]	[%]	[%]	[%]
1	Maldives‡	0.12	19	3.5	28.5	52.96	1.46	53.65
2	Fiji‡	0.18	53	1.9	11.0	15.84	0.31	16.10
3	Croatia	0.23	69	2.7	11.5	13.67	0.25	13.89
4	Cambodia*	0.31	56	3.9	13.2	11.90	0.56	12.39
5	Montenegro	0.24	71	2.1	9.4	10.99	0.18	11.15
6	Belize‡	0.27	58	2.7	10.2	10.26	0.37	10.59
7	Kuwait*	3.53	25	7.9	1.7	7.59	2.73	10.11
8	Bahamas‡	0.32	65	3.3	11.0	9.37	0.36	9.69
9	Jordan*	0.30	32	2.0	7.2	6.58	0.56	7.10
10	Jamaica‡*	0.36	55	2.9	8.9	6.47	0.44	6.88
11	Malta	0.38	43	3.9	9.8	6.08	0.83	6.86
12	Panama*	0.34	55	2.7	7.9	5.91	0.40	6.28
13	Hong Kong*	0.58	33	7.2	12.6	3.31	2.01	5.25
14	Brunei Darussalam*	2.39	33	5.7	1.8	3.44	1.56	4.94
15	Cyprus	0.64	14	6.2	9.6	1.63	3.04	4.62
16	Mauritius‡*	0.47	53	3.9	8.8	4.02	0.62	4.61
17	Albania	0.92	13	8.4	10.2	0.16	4.15	4.30
18	Dominican Republic‡*	0.36	73	2.0	5.8	4.06	0.16	4.21
19	Georgia	0.44	49	2.7	6.8	3.52	0.49	3.99
20	Greece	0.48	72	3.6	7.7	3.18	0.30	3.47
21	Thailand*	0.43	65	2.7	6.1	3.01	0.29	3.29
22	Qatar*	1.18	14	5.9	3.8	0.36	2.89	3.23
23	Armenia	1.09	11	6.1	6.2	-0.01	3.24	3.23
24	Zimbabwe*	2.42	0	1.3	0.6	0.63	2.15	2.76
25	Bulgaria	0.47	45	2.3	5.0	2.13	0.46	2.58
26	Morocco*	0.48	64	2.5	5.5	2.30	0.29	2.58
27	Costa Rica*	0.51	73	3.2	6.4	2.26	0.26	2.52
28	Portugal	0.52	60	3.2	6.2	2.03	0.42	2.44
29	Saudi Arabia*	1.76	32	3.9	2.0	1.09	1.12	2.20
30	Tunisia*	0.54	71	2.9	5.7	1.79	0.25	2.03
31	St. Vincent & Gren.‡	0.32	66	0.7	2.4	1.88	0.08	1.96
32	Estonia	0.68	28	3.7	5.4	0.70	1.17	1.86
33	Norway	1.62	39	4.2	2.4	0.85	0.97	1.82
34	Iceland	0.79	38	6.2	7.5	0.32	1.50	1.81
35	Singapore‡*	1.18	28	4.8	3.7	0.20	1.54	1.74
36	Puerto Rico‡	0.64	74	5.0	7.8	1.37	0.38	1.74
37	Luxembourg	0.69	20	3.4	4.3	0.34	1.36	1.70
38	Kenya*	0.61	92	3.4	6.4	1.55	0.07	1.62
39	Azerbaijan	1.11	31	5.2	4.1	0.12	1.49	1.60
40	El Salvador*	0.56	78	2.4	4.7	1.41	0.15	1.56
41	Belgium	1.47	25	3.3	2.2	0.41	1.13	1.53
42	Turkey*	0.51	84	2.0	4.0	1.38	0.09	1.47
43	Yemen*	0.60	90	3.0	5.6	1.38	0.08	1.46
44	Tanzania*	0.70	39	3.3	5.1	0.68	0.77	1.45
45	Kyrgyz Republic	1.16	24	4.0	4.2	-0.03	1.44	1.41
46	Lesotho*	1.77	52	3.9	2.5	0.78	0.63	1.41
47	Slovenia	0.59	55	2.7	4.5	0.97	0.41	1.37
48	United Arab Emirates*	1.17	30	4.2	3.6	0.10	1.24	1.34
49	Nigeria*	1.62	59	4.1	2.6	0.78	0.55	1.32
50	Ukraine	1.63	34	2.8	1.7	0.52	0.74	1.26
51	Botswana*	0.55	68	2.2	3.9	1.03	0.21	1.24

Continued on next page

Table B.3 – continued from previous page

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Country	X_j/Y_j	λ_{jj}	α_j	γ_j	$\widehat{W}_{j,w}$	$\widehat{W}_{j,\lambda_{jj}}$	\widehat{W}_j
		[-]	[%]	[%]	[%]	[%]	[%]	[%]
52	Laos*	0.76	42	3.7	5.2	0.44	0.80	1.24
53	Russian Federation	1.64	40	2.8	1.7	0.59	0.65	1.23
54	Mongolia	1.58	28	2.5	1.6	0.40	0.78	1.18
55	Togo*	0.47	61	1.1	2.4	1.04	0.13	1.18
56	Myanmar*	0.41	89	0.9	2.2	1.13	0.03	1.16
57	Hungary	0.59	61	2.4	3.9	0.83	0.30	1.13
58	Spain	0.65	79	3.6	5.4	0.87	0.21	1.07
59	Bahrain*	0.61	47	2.6	3.7	0.58	0.49	1.06
60	Vanuatu†*	0.18	25	0.1	0.7	1.01	0.05	1.06
61	Moldova	1.26	28	3.0	2.8	0.05	0.94	0.99
62	Ireland	0.65	32	1.9	2.6	0.34	0.53	0.86
63	Philippines*	1.21	62	5.7	4.8	0.17	0.68	0.85
64	Uganda*	0.63	50	1.7	2.8	0.55	0.29	0.84
65	Oman*	1.03	37	3.2	2.6	0.02	0.81	0.83
66	Bolivia*	1.13	52	4.4	3.9	0.07	0.72	0.79
67	Denmark	1.18	42	3.2	2.6	0.10	0.69	0.79
68	Malaysia*	0.73	55	3.1	4.0	0.32	0.46	0.78
69	Austria	0.77	67	4.3	5.5	0.33	0.42	0.75
70	Iraq*	1.28	49	2.9	2.1	0.22	0.52	0.75
71	Gambia*	0.58	42	1.1	2.0	0.48	0.25	0.73
72	Vietnam*	0.68	74	2.7	3.9	0.48	0.21	0.69
73	Uruguay*	0.91	42	2.9	3.3	0.03	0.64	0.67
74	New Zealand	0.79	75	4.8	6.0	0.30	0.35	0.65
75	Sri Lanka*	0.74	51	2.2	3.0	0.27	0.37	0.63
76	Serbia	1.00	33	2.3	2.4	0.00	0.62	0.62
77	Germany	1.14	74	6.4	5.4	0.14	0.47	0.61
78	Switzerland	0.96	47	3.2	3.1	0.00	0.61	0.61
79	Netherlands	1.11	44	2.7	2.3	0.04	0.55	0.59
80	Sweden	1.12	58	3.9	3.4	0.06	0.52	0.58
81	Latvia	0.84	47	2.5	3.0	0.10	0.47	0.56
82	Canada	1.26	59	3.1	2.4	0.15	0.41	0.56
83	Nepal*	1.13	53	3.5	3.7	-0.02	0.56	0.54
84	Nicaragua*	0.92	62	3.9	4.7	0.07	0.47	0.54
85	United Kingdom	1.07	72	6.1	5.7	0.02	0.49	0.52
86	Namibia*	0.76	87	3.2	4.6	0.40	0.11	0.51
87	Lithuania	0.86	47	2.4	2.8	0.06	0.45	0.51
88	Egypt*	0.79	79	3.5	4.7	0.29	0.20	0.49
89	Cameroon*	1.12	57	3.2	3.0	0.03	0.46	0.49
90	Macedonia	0.76	49	1.6	2.3	0.19	0.29	0.48
91	Czech Republic	0.79	43	1.7	2.1	0.10	0.35	0.45
92	Poland	0.81	33	1.3	1.6	0.06	0.36	0.43
93	Ghana*	0.96	53	2.5	2.8	0.01	0.40	0.41
94	Slovak Republic	1.00	48	2.2	2.2	0.00	0.41	0.41
95	Finland	1.15	58	2.6	2.2	0.05	0.35	0.40
96	Honduras*	0.94	74	4.4	5.1	0.05	0.34	0.39
97	Guyana†*	0.99	63	3.3	3.8	0.01	0.37	0.38
98	Suriname†	0.92	38	1.5	1.7	0.02	0.35	0.37
99	France	0.96	67	3.6	3.8	0.01	0.36	0.37
100	China*	1.22	67	2.6	2.1	0.10	0.26	0.37
101	Guatemala*	0.86	69	2.9	3.5	0.10	0.26	0.36
102	South Africa	0.81	64	2.1	2.7	0.12	0.24	0.36
103	Paraguay*	1.14	60	2.4	2.1	0.04	0.30	0.34
104	Sao Tome and Principe†*	0.41	27	0.2	0.5	0.27	0.07	0.34
105	Belarus	1.02	66	3.1	3.1	0.00	0.33	0.33
106	Burundi*	1.41	68	1.9	1.4	0.15	0.18	0.33
107	Iran*	1.26	65	2.1	1.7	0.10	0.23	0.33

Continued on next page

Table B.3 – continued from previous page

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Country	X_j/Y_j	λ_{jj}	α_j	γ_j	$\widehat{W}_{j,w}$	$\widehat{W}_{j,\lambda_{jj}}$	\widehat{W}_j
		[-]	[%]	[%]	[%]	[%]	[%]	[%]
108	Benin*	0.68	74	1.1	1.7	0.25	0.08	0.33
109	Senegal*	0.85	75	2.8	3.5	0.13	0.19	0.32
110	Australia	0.98	70	3.4	3.5	0.00	0.31	0.31
111	Venezuela*	1.10	89	7.7	6.8	0.09	0.22	0.31
112	Brazil*	1.22	76	2.9	2.4	0.10	0.20	0.30
113	Zambia*	0.78	60	1.5	1.9	0.10	0.19	0.29
114	Burkina Faso*	0.98	48	1.6	1.7	0.00	0.29	0.29
115	Argentina*	1.05	83	5.8	5.5	0.02	0.27	0.29
116	Korea, Rep.*	1.05	63	2.4	2.2	0.01	0.27	0.28
117	Colombia*	1.02	60	2.0	2.0	0.00	0.26	0.26
118	Peru*	0.87	82	3.5	4.1	0.08	0.17	0.25
119	Italy	0.88	77	3.3	3.6	0.05	0.21	0.25
120	Ecuador*	0.83	54	1.3	1.6	0.05	0.19	0.25
121	Romania	1.07	55	1.5	1.4	0.01	0.23	0.24
122	Mozambique*	1.12	66	2.5	2.6	-0.02	0.25	0.23
123	Kazakhstan	1.08	67	1.8	1.5	0.02	0.18	0.20
124	Malawi*	1.18	77	2.4	2.2	0.03	0.16	0.19
125	United States	0.91	85	3.6	4.0	0.04	0.14	0.19
126	Sudan*	0.83	84	2.1	2.6	0.09	0.09	0.19
127	Mexico*	0.97	90	6.3	6.5	0.01	0.16	0.17
128	Indonesia*	0.97	78	2.6	2.7	0.00	0.16	0.16
129	Chile*	0.97	83	3.3	3.4	0.00	0.15	0.15
130	Pakistan*	1.11	83	2.9	2.7	0.02	0.14	0.15
131	India*	0.97	84	2.6	2.7	0.00	0.11	0.12
132	Bangladesh*	1.08	91	2.8	2.7	0.01	0.06	0.07
133	Japan	1.04	87	1.9	1.9	0.00	0.07	0.07
134	Algeria*	1.04	92	2.3	2.3	0.00	0.05	0.05
135	Sierra Leone*	0.92	82	0.4	0.5	0.00	0.02	0.03

Notes: Small island developing states indicated by a ‡. Developing countries indicated by a *.

Appendix C

Appendix to Chapter 6

C.1 Mathematical appendix

PROOF OF PROPOSITION 1

From the definition of the budget shares in 6.8 and expenditure functions in 6.3, the budget shares can be written for the initial equilibrium state as

$$\begin{aligned}\lambda_a^h &= \frac{X_a^h}{X_j^h} = \frac{X_a^h}{\sum_{i=1}^I X_a^h} = \frac{\left(w_i^h \tau_a^h\right)^{\epsilon^h} X_j^h \left(P_j^h\right)^{-\epsilon^h} \mathbf{S}_i}{\sum_{i=1}^I \left(w_i^h \tau_a^h\right)^{\epsilon^h} X_j^h \left(P_j^h\right)^{-\epsilon^h} \mathbf{S}_i} \\ &= \frac{\left(w_i^h \tau_a^h\right)^{\epsilon^h} \mathbf{S}_i}{\sum_{i=1}^I \left(w_i^h \tau_a^h\right)^{\epsilon^h} \mathbf{S}_i}.\end{aligned}$$

In the new equilibrium, these budget shares take the form

$$\lambda_a^{h'} = \frac{\left(w_i^{h'} \tau_a^{h'}\right)^{\epsilon^h} \mathbf{S}_i'}{\sum_{i=1}^I \left(w_i^{h'} \tau_a^{h'}\right)^{\epsilon^h} \mathbf{S}_i'}.$$

Dividing $\lambda_a^{h'}$ by λ_a^h and using Definition 1

$$\hat{\lambda}_a^h = \frac{\left(\hat{w}_i^h \hat{\tau}_a^h\right)^{\epsilon^h}}{\sum_{i=1}^I \lambda_a^h \left(\hat{w}_i^h \hat{\tau}_a^h\right)^{\epsilon^h}}, \quad \text{where } a = \{ij, ji\}.$$

Market clearing (using 6.7) in the new equilibrium implies $Y_i^{h'} = \sum_j X_a^{h'} = \sum_j \lambda_{ij}^{h'} X_j^{h'}$ as

well as $Y_i^{h'} = \sum_j \lambda'_{ji} X_j^{h'}$ respectively. Changes in income can therefore be written as

$$\hat{Y}_i^h = \frac{1}{Y_i^h} \sum_j \hat{\lambda}_a \lambda_a \hat{X}_j^h X_j^h, \quad a = \{ij, ji\}.$$

The next step requires to link changes in sector h to changes of the entire economy in each country. From Equation 6.9, a country's change in total income from all sectors is given by

$$Y_i = w_i L_i \equiv L_i \prod_{h=1}^H \left(w_i^h \right)^{\gamma_j^h} \iff \hat{Y}_i = \prod_{h=1}^H \left(\hat{w}_i^h \right)^{\gamma_i^h},$$

where the second equality derives from the fact that labour L remains constant by Definition 1. If only one sector changes at a time, this equality simplifies to $\hat{Y}_i = \left(\hat{w}_i^h \right)^{\gamma_i^h}$.

Using Equation 6.11, a country's change in total income can be linked to its change in total expenditure using

$$X_i = w_i L_i (1 + d_n) \iff \hat{X}_i = \hat{w}_i.$$

Because market clearing implies $Y_i = w_i L_i$ (Equation 6.9) it follows that $\hat{Y}_i = \hat{w}_i$. Combining this observation with the previous one results into $\hat{X}_i = \hat{w}_i = \hat{Y}_i$.

Assuming that a change in a country's overall income equivalently applies to all sectors $\hat{X}_i^h \equiv \hat{X}_i$ and therefore $\hat{X}_i^h = \hat{Y}_i = \left(\hat{w}_i^h \right)^{\gamma_i^h}$, the expression for the changes in budget shares of sector h can be rewritten as a general equilibrium model that iterates over the vector of wages $\mathbf{w} \equiv \{w_i^h\}$ in sector h

$$\begin{aligned} \hat{w}_i^h &= \frac{1}{Y_i^h} \sum_j \hat{\lambda}_a \lambda_a \left(\hat{w}_j^h \right)^{\gamma_i^h} X_j^h \\ &= \frac{1}{Y_i^h} \sum_j \frac{\lambda_a^h \left(\hat{w}_i^h \hat{\tau}_a^h \right)^{\epsilon^h}}{\sum_{i=1}^I \lambda_a^h \left(\hat{w}_i^h \hat{\tau}_a^h \right)^{\epsilon^h}} \left(\hat{w}_j^h \right)^{\gamma_i^h} X_j^h, \quad a = \{ij, ji\}, \end{aligned}$$

which is Equation 6.19 in Section 6.2. ■

PROOF OF PROPOSITION 2

Transferring the transport cost function $C_\tau = \zeta(y, \boldsymbol{\vartheta}, \mathbf{P}, F, \xi(t))$ in 6.12 into a logarithmic form and taking the total differential of the log of variable costs with respect to factor

input prices $\mathbf{P} \equiv \{P_k\}$ yields

$$\begin{aligned} \frac{d \ln C_\tau}{d \ln P_k} &= \frac{\partial \ln C_\tau}{\partial \ln y} \frac{d \ln y}{d \ln P_k} + \sum_q \frac{\partial \ln C_\tau}{\partial \ln \vartheta_q} \frac{d \ln \vartheta_q}{d \ln P_k} + \sum_i \frac{\partial \ln C_\tau}{\partial \ln P_k} + \\ &\quad \frac{\partial \ln C_\tau}{\partial \ln F} \frac{d \ln F}{d \ln P_k} + \frac{\partial \ln C_\tau}{\partial \ln \xi(t)} \frac{d \ln \xi(t)}{d \ln P_k}. \end{aligned}$$

The partial derivatives in this expression represent the cost elasticities with respect to output ($\varepsilon_y \equiv \partial \ln C_\tau / \partial \ln y$), any quality differentials ($\varepsilon_\vartheta^q \equiv \partial \ln C_\tau / \partial \ln \vartheta_q$), fixed inputs ($\varepsilon_F \equiv \partial \ln C_\tau / \partial \ln F$), technology ($\partial \ln C_\tau / \partial \ln \xi(t)$), and input prices $\partial \ln C_\tau / \partial \ln p_i$. In addition, the cost elasticity with respect to prices is representative for the cost share of the respective variable factor input (indexed with an i).

The expression above can be investigated for any changes in input prices

$\mathbf{P} = [P_{\text{fuel}}, P_{\text{labour}}, P_{\text{material}}, \dots, P_k]$. By Definition 1 however, only changes in the fuel price index are of primary interest for the general equilibrium model used in this study. With $P_k = P_{\text{fuel}}$, the fuel cost share of the variable cost function is given by $\lambda_{\text{fuel}} \equiv \partial \ln C_\tau / \partial \ln p_i$.

Because a transport firm is assumed to operate under CRS (see main text), average costs equal marginal costs, the cost elasticity with respect to output can be set to one ($\varepsilon_y = 1$), and the output variable y be taken to the left hand side of the cost function to obtain Equation 6.13 in the main text.

As pure technical change causes a neutral shift of the entire production function, the general index of pure technical technical change $\xi(t)$ can be expressed as a time-dependent constant. As a result, the elasticity of cost with respect to pure technical change must be equal to one $\partial \ln C / \partial \ln \xi(t) = 1$.

Combining these observations in the expression from above

$$\frac{d \ln C_\tau}{d \ln P_{\text{fuel}}} = \frac{d \ln y}{d \ln P_{\text{fuel}}} + \sum_q \varepsilon_\vartheta^q \frac{d \ln \vartheta_q}{d \ln P_{\text{fuel}}} + \lambda_{\text{fuel}} + \varepsilon_F \frac{d \ln F}{d \ln P_{\text{fuel}}} + \frac{d \ln \xi(t)}{d \ln P_{\text{fuel}}}$$

and rearranging yields

$$d \ln \left(\frac{C_\tau}{y} \right) = \lambda_{\text{fuel}} d \ln P_{\text{fuel}} + \sum_q \varepsilon_\vartheta^q d \ln \vartheta_q + \varepsilon_F d \ln F + d \ln \xi(t).$$

Integrating this expression between a point in time t and $t + 1$, which correspond to a situation before and after a carbon tax on international transport has been introduced and noting that, by Definition 1, this transition corresponds to any changes in costs, output related quality differentials and technology that do not affect output $\hat{y} = 1$ as well as fixed

costs¹ $\widehat{F} = 1$ results into

$$\begin{aligned} \ln \left(\frac{C'_\tau}{y'} \right) - \ln \left(\frac{C_\tau}{y} \right) &= \lambda_{\text{fuel}} (\ln P'_{\text{fuel}} - \ln P_{\text{fuel}}) + \sum_q \varepsilon^q_{\vartheta} (\ln \vartheta'_q - \ln \vartheta_q) + \\ &\quad \varepsilon_F (\ln F' - \ln F) + \ln \xi(t+1) - \ln \xi(t) \iff \\ \frac{\widehat{C}_\tau}{\widehat{y}} &= (\widehat{P}_{\text{fuel}})^{\lambda_{\text{fuel}}} (\widehat{F})^{\varepsilon_F} \frac{\xi(t+1)}{\xi(t)} \prod_q (\widehat{\vartheta}_q)^{\varepsilon^q_{\vartheta}} \iff \\ \widehat{C}_\tau &= (\widehat{P}_{\text{fuel}})^{\lambda_{\text{fuel}}} \xi \prod_q (\widehat{\vartheta}_q)^{\varepsilon^q_{\vartheta}}, \end{aligned}$$

where the left hand side has been transformed to only account for changes in transport costs as transport output y remains constant by Definition 1. From this expression, which is Equation 6.20 in the main text, $\xi(t)$ can now be recovered as a general index of pure technical technical change at time t , while $\dot{\xi} \equiv \xi(t+1)/\xi(t)$ measures the rate of pure technical change². Within the stated time period, technological progress thus occurred if $\dot{\xi} < 1$, whereas $\dot{\xi} > 1$ indicates technological regress. ■

PROOF OF PROPOSITION 3

Equation 6.1 can be used to link changes in freight rates and airfares \widehat{f}_a^h to changes in iceberg transport costs $\widehat{\tau}_a^h$ using $\tau_a = 1 + f_a/w_i \geq 1$, where $a = \{ij, ji\}$. As the formulation of iceberg transport costs includes a normalisation using wages, which change in moving from the initial to the new equilibrium, it is necessary to also keep track of the changes in wages in this derivation.

Under constant markups, changes in prices charged by a transport firm are given by $\widehat{f}_a^h = \widehat{C}_\tau^h$. Changes in freight rates and airfares in the new equilibrium can thus be written as $f_a^{h'} = f_a^h \widehat{C}_\tau^h$. Dropping the index h to ease notation, changes in iceberg freight rates and airfares can then be calculated using

$$\begin{aligned} \widehat{\tau}_a &= \frac{1 + \frac{f'_a}{w'_i}}{1 + \frac{f_a}{w_i}} = \frac{\frac{w'_i + f'_a \widehat{C}_\tau}{w'_i}}{\frac{w_i + f_a}{w_i}} = \frac{w_i (w'_i + f_a \widehat{C}_\tau)}{w'_i \underbrace{(w_i + f_a)}_{p_a}} \\ &= \frac{w_i}{w'_i p_a} (w'_i + f_a \widehat{C}_\tau) = \frac{w_i}{p_a} + \frac{w_i}{w'_i} \frac{f_a}{p_a} \widehat{C}_\tau \\ &= \frac{1}{\tau_a} + \frac{1}{\widehat{w}_i} \frac{f_a}{p_a} \widehat{C}_\tau, \quad a = \{ij, ji\}. \end{aligned}$$

¹Faced with a permanent change in fuel cost, a transport firm will consider to invest into more fuel-efficient technology over time. These changes are captured by $\dot{\xi}$. High capital investments costs and the related difficulties to adjust to new cost-optimal minima over a relatively short period of time could also involve a in fixed costs F . These changes are not taken into account.

²See e.g. Lundmark and Söderholm, 2004 for a similar specification of the rate of pure technical change.

In addition, one can show that

$$\frac{1}{\tau_a} = \frac{1}{1 + \frac{f_a}{w_i}} = \frac{1}{1 + \frac{f_a}{p_a - f_a}} = \frac{1}{\frac{p_a}{p_a - f_a}} = \frac{p_a - f_a}{p_a} = 1 - \frac{f_a}{p_a}, \quad a = \{ij, ji\}.$$

Combining both expressions and multiplying both sides with \widehat{w}_i yields

$$\widehat{w}_i \widehat{\tau}_a = \widehat{w}_i \left(1 - \frac{f_a}{p_a}\right) + \widehat{C}_\tau \left(\frac{f_a}{p_a}\right), \quad a = \{ij, ji\},$$

which is Equation 6.21 in the main text. ■

PROOF OF PROPOSITION 4

Starting from the price index

$$P_j^h = \left(\sum_{i=1}^I \left(w_i^h \tau_a^h \right)^{\epsilon^h} \mathbf{S}_i \right)^{1/\epsilon^h} \iff$$

$$\left(P_j^h \right)^{\epsilon^h} = \sum_{i=1}^I \left(w_i^h \tau_a^h \right)^{\epsilon^h} \mathbf{S}_i, \quad a = \{ij, ji\}$$

it follows that small changes in the price index satisfy

$$\epsilon^h d \ln P_j^h = \sum_{i=1}^I \lambda_a^h \epsilon^h \left(d \ln w_i^h + d \ln \tau_a^h \right) \iff$$

$$d \ln P_j^h = \sum_{i=1}^I \lambda_a^h \left(d \ln w_i^h + d \ln \tau_a^h \right), \quad a = \{ij, ji\}.$$

From the gravity equations given by Equation 6.3, the budget shares λ_a^h can be rewritten as

$$X_a^h / X_j^h = \lambda_a^h = \left(w_i^h \tau_a^h \right)^{\epsilon^h} \left(P_j^h \right)^{-\epsilon^h} \mathbf{S}_i, \quad a = \{ij, ji\},$$

and also be stated for domestic flows in the form of (noting that $\tau_{jj}^h = 1$)

$$X_{jj}^h / X_j^h = \lambda_{jj}^h = \left(w_j^h \right)^{\epsilon^h} \left(P_j^h \right)^{-\epsilon^h} \mathbf{S}_j.$$

Relative spending is therefore given by

$$\lambda_a^h / \lambda_{jj}^h = \left(w_i^h \tau_a^h / w_j^h \right)^{\epsilon^h} \mathbf{S}_i / \mathbf{S}_j, \quad a = \{ij, ji\}.$$

Taking logs of this expression gives

$$d \ln \lambda_a^h - d \ln \lambda_{jj}^h = \epsilon^h \left(d \ln w_i^h + d \ln \tau_a^h - d \ln w_j^h \right) \mathbf{S}_i / \mathbf{S}_j \iff$$

$$\frac{d \ln \lambda_a^h - d \ln \lambda_{jj}^h}{\epsilon^h} + d \ln w_j^h = d \ln w_i^h + d \ln \tau_a^h, \quad a = \{ij, ji\},$$

because $d \ln \mathbf{S}_i = 0$ and $d \ln \mathbf{S}_j = 0$.

Combining these results with the expression for the changes in the price index, it can be shown that

$$\begin{aligned} d \ln P_j^h &= \sum_{i=1}^I \lambda_a^h \left(\frac{d \ln \lambda_a^h - d \ln \lambda_{jj}^h}{\epsilon^h} + d \ln w_j^h \right) \\ d \ln P_j^h &= \frac{\sum_{i=1}^I \lambda_a^h (d \ln \lambda_a^h - d \ln \lambda_{jj}^h)}{\epsilon^h} + \sum_{i=1}^I \lambda_a^h d \ln w_j^h, \quad a = \{ij, ji\}. \end{aligned}$$

Because $\sum_{i=1}^I \lambda_a^h = 1$ by definition 6.8 and therefore $\sum_{i=1}^I d \ln \lambda_a^h = 0$ it follows that

$$d \ln P_j^h = \frac{-d \ln \lambda_{jj}^h}{\epsilon^h} + d \ln w_j^h,$$

which is Equation 6.2 in the main text. ■

C.2 Data appendix

Using a similar specification as in Simonovska and Waugh (2014) (online appendix), gross industry output and gross output values for the countries not included in the OECD Input Output tables are approximated using the ratio of value added to gross output. The specification used for the industry sector is

$$\ln \left(\frac{\text{GDP}^I}{Y^I} \right) = \beta_0 + \beta_{\text{GDP}} C_{\text{GDP}} + \beta_{\text{POP}} C_{\text{POP}} + \sum_{k=1}^{i,a} \left(\beta_L^k C_l^k + \beta_{\text{GDP}}^k C_{\text{GDP}}^k \right) + \varepsilon,$$

and for the total economy

$$\ln \left(\frac{\text{GDP}}{Y} \right) = \beta_0 + \beta_{\text{GDP}} C_{\text{GDP}} + \beta_{\text{POP}} C_{\text{POP}} + \sum_{k=1}^{i,a,s} \left(\beta_L^k C_l^k + \beta_{\text{GDP}}^k C_{\text{GDP}}^k \right) + \varepsilon,$$

where β_x is 1×3 vector of coefficients corresponding to C_x . C_x denotes an $N \times 3$ matrix of variables containing $\left[\ln(x), (\ln(x))^2, (\ln(x))^3 \right]$ for the sub-sample of N countries for which data is available. POP refers to total population and L to the labour force in each sector in each country using data from the World Bank. The World Bank uses the sector disaggregation of industry (i), agriculture (a), and services (s), where industry corresponds to ISIC divisions 10-45 and agriculture to ISIC divisions 1-5. Jointly, the World Bank sectors i and a therefore represent the industry sector I as defined in Chapter 6, whereas,

all three World Bank sectors (i , a and s) represent the entire economy. The labour force in each sector is calculated by multiplying labour share data in each sector (i , a and s) with total labour force data from the World Bank.

Calculated and estimated 2011 gross output and gross industry output values are then transferred to 2014 values using 2011-14 growth rates in industry GDP and total GDP and corrected for inflation with data from the World Bank.

Rate of CO₂ reduction. The rate of CO₂ reduction is approximated using marginal abatement cost curve data from Schäfer et al. (2015) for aviation and from Alvik et al. (2009) for maritime transport. In both cases, a constant value is added to the marginal abatement costs such that negative values do not occur and emission reductions are normalised to represent % emission reductions of the entire fleet. Using this data, a power function, constrained to pass through the zero-point, in the form of

$$\phi^h(P_{CO_2}) = \% \text{ CO}_2 \text{ reduction} = 1 - \left(\frac{\beta_2}{\text{carbon price} + \beta_2} \right)^{\beta_1} \quad (C.1)$$

is fitted, using nonlinear least squares. Figure C.1 shows the data, the estimated coefficients, and the fitted curve. To establish MAC curves, the cost-effective mitigation options are assumed to be implemented first. The rate of CO₂ reduction in Figure C.1 therefore declines with higher carbon prices, as the basket of cost-effective mitigation options is gradually exhausted, leaving mitigation options that are more expensive to implement. The maritime transport industry has—in comparison to the air transport industry—a significantly larger number of mitigation options with significantly higher CO₂ abatement potential available. The potential for emission reductions is therefore lower in the aviation than in the maritime transport industry, as indicated by the data in Figure C.1.

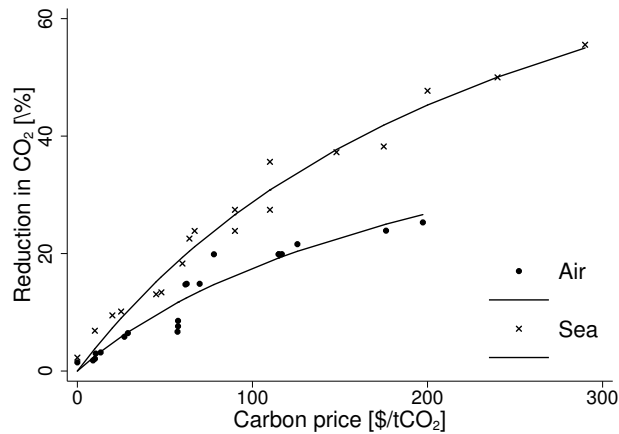


Figure C.1: Approximated rate of CO₂ reduction in the aviation and maritime transport industry. Data from Schäfer et al. (2015) and Alvik et al. (2009). Aviation: $\beta_1 = 0.32$, and $\beta_2 = 121$. Maritime transport: $\beta_1 = 1.18$, and $\beta_2 = 301$.

C.3 Additional results and figures

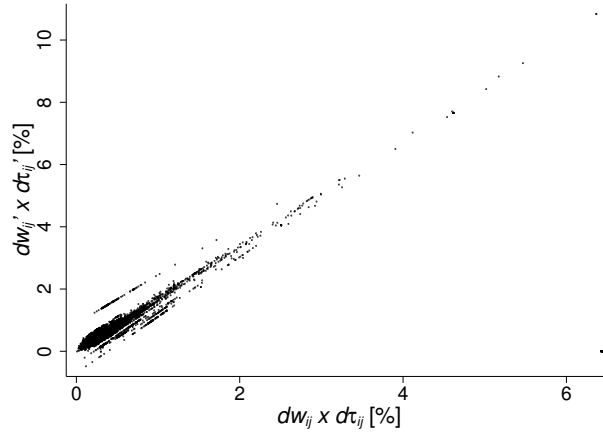


Figure C.2: Dynamic price changes in trade. The figure displays the changes in prices p_{ji}^I (of all country pairs in the dataset) between the initial and new equilibrium as a result of changes in wages \hat{w}^I in international trade using a carbon price of \$50/tCO₂.

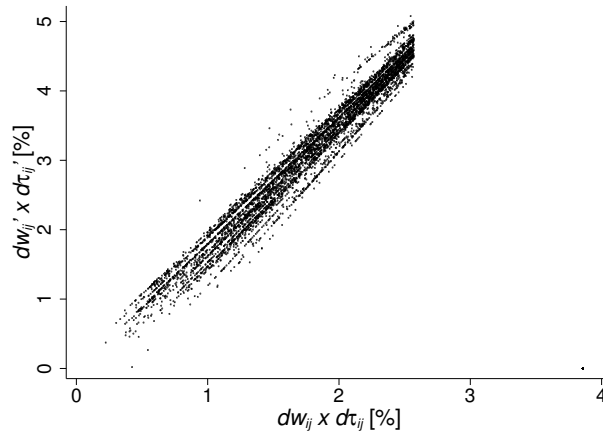


Figure C.3: Dynamic price changes in tourism. As in Figure C.2 but for tourism, using a carbon price of \$50/tCO₂.

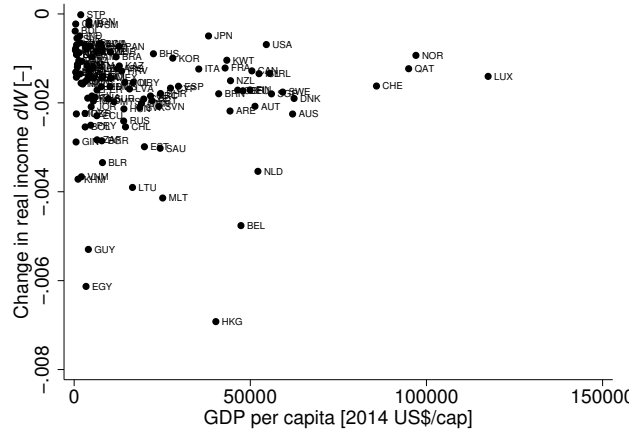


Figure C.4: Reductions in real income $\widehat{W}_j - 1$ by country due to a carbon price of \$300/tCO₂ in international sea transport.

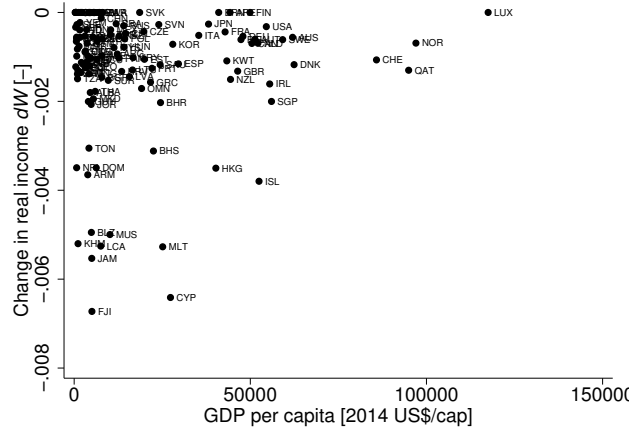


Figure C.5: Reductions in real income $\widehat{W}_j - 1$ by country due to a carbon price of \$300/tCO₂ in international air transport.

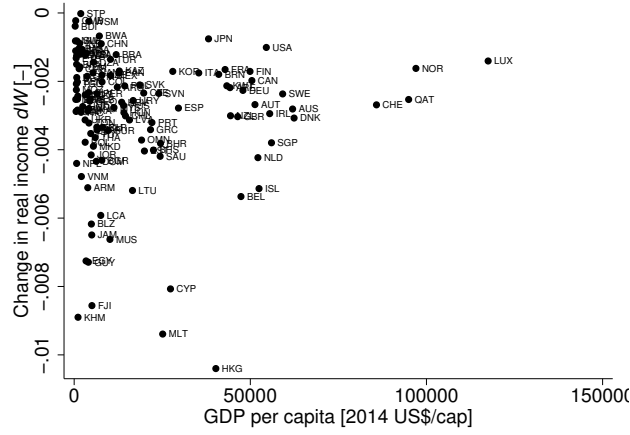


Figure C.6: Reductions in real income $\widehat{W}_j - 1$ by country due to a carbon price of \$300/tCO₂ in international air and sea transport.

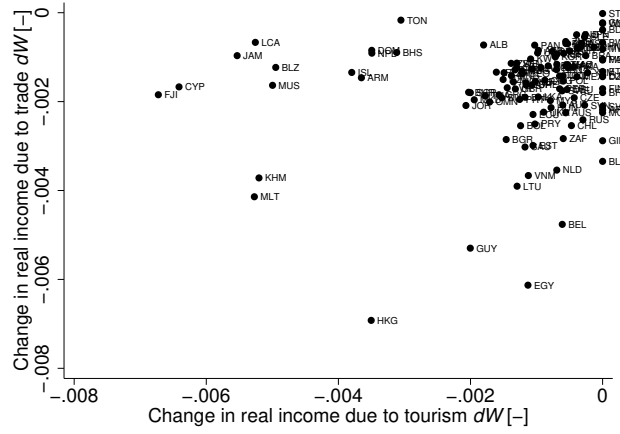


Figure C.7: Reductions in real income $\widehat{W}_j - 1$ of trade against tourism due to a carbon price of \$300/tCO₂ in international air and sea transport.

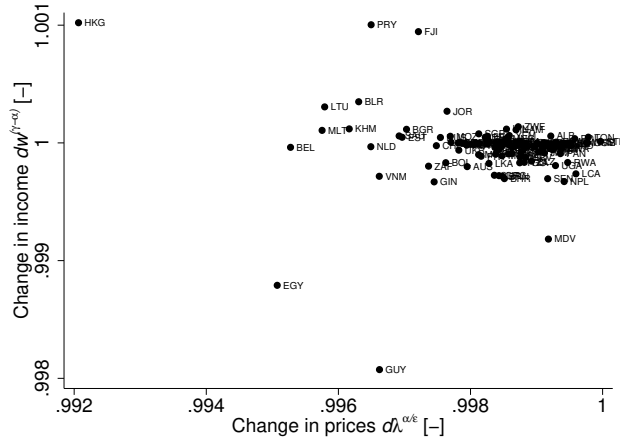


Figure C.8: Changes in income $\left(\widehat{W}_j^h\right)^{(\gamma_j^h - \alpha_j^h)}$ over changes in the price index $\left(\widehat{\lambda}_{jj}^h\right)^{\alpha_j^h / \epsilon^h}$ in the industry sector due to a carbon price of \$300/tCO₂ in international sea transport.

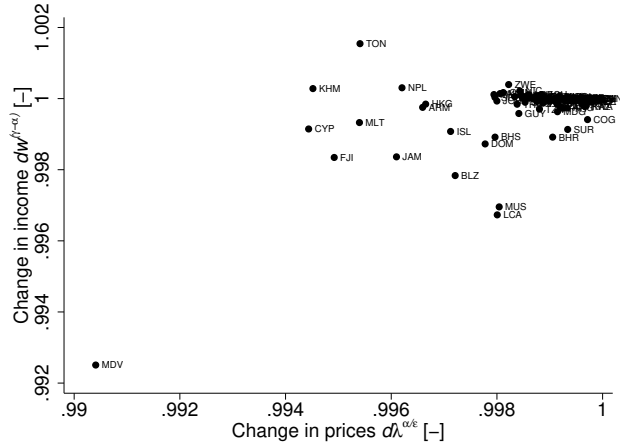


Figure C.9: Changes in income $\left(\widehat{W}_j^h\right)^{(\gamma_j^h - \alpha_j^h)}$ over changes in the price index $\left(\widehat{\lambda}_{jj}^h\right)^{\alpha_j^h / \epsilon^h}$ in the tourism sector due to a carbon price of \$300/tCO₂ in international air transport.

Table C.1: Sensitivity analysis of results in Table 6.3 using lower demand elasticities

(1) Carbon price \$/tCO ₂	(2) Av. \hat{p}_{ij}^I %	(3) Av. $\hat{\lambda}_{jj}^I$ %	(4) Av. delta RI \$/cap.	(5) Delta GWP \$bn	(6) Tax rev. \$bn	(7) Delta CO₂ MtCO ₂	(8) Economic cost \$GWP/tCO ₂
International trade in a CO ₂ -constrained world							
25	.3	.3	-15	-24	13	-52	464
50	.5	.6	-26	-42	24	-96	440
75	.7	.8	-35	-56	33	-133	418
100	.9	.9	-41	-66	41	-166	398
125	1	1	-46	-74	48	-194	379
150	1	1.1	-50	-79	53	-219	363
175	1.1	1.1	-52	-84	58	-241	347
200	1.1	1.2	-54	-87	63	-260	333
225	1.2	1.2	-56	-89	67	-278	320
250	1.2	1.2	-57	-90	70	-294	308
275	1.2	1.3	-57	-91	73	-308	297
300	1.2	1.3	-59	-94	78	-316	298
International tourism in a CO ₂ -constrained world							
25	1.7	1.3	-5	-8	10	-26	295
50	3.1	2.3	-9	-14	20	-46	295
75	4.3	3.2	-12	-18	28	-63	293
100	5.3	3.9	-15	-22	36	-77	292
125	6.1	4.5	-17	-26	44	-89	291
150	6.9	5.1	-19	-29	51	-100	289
175	7.5	5.6	-20	-31	58	-109	288
200	8.1	6	-22	-34	64	-117	286
225	8.6	6.3	-23	-36	70	-125	285
250	9.1	6.7	-24	-37	76	-132	283
275	9.5	7	-25	-39	82	-138	282
300	9.9	7.3	-26	-40	88	-144	280
International trade and tourism in a CO ₂ -constrained world							
25	-	-	-20	-32	23	-77	409
50	-	-	-35	-56	44	-142	393
75	-	-	-47	-74	61	-196	378
100	-	-	-56	-88	77	-242	364
125	-	-	-63	-99	91	-283	351
150	-	-	-68	-108	104	-318	340
175	-	-	-73	-115	116	-350	329
200	-	-	-76	-120	127	-378	318
225	-	-	-79	-124	137	-403	309
250	-	-	-81	-128	147	-426	300
275	-	-	-82	-130	156	-446	292
300	-	-	-85	-134	166	-460	292

Notes: The base year for calculations is 2014 using data and input parameters as specified in Table 6.1 and $\epsilon^I = -3$ and $\epsilon^T = -2$.

Table C.2: Sensitivity analysis of results in Table 6.3 using higher demand elasticities

(1) Carbon price \$/tCO ₂	(2) Av. \hat{p}_{ij}^I %	(3) Av. $\hat{\lambda}_{jj}^I$ %	(4) Av. delta RI \$/cap.	(5) Delta GWP \$bn	(6) Tax rev. \$bn	(7) Delta CO₂ MtCO ₂	(8) Economic cost \$GWP/tCO ₂
International trade in a CO ₂ -constrained world							
25	.3	.8	-15	-24	13	-52	463
50	.5	1.3	-26	-42	24	-96	435
75	.7	1.8	-34	-55	33	-133	411
100	.9	2.1	-40	-65	41	-166	390
125	1	2.3	-45	-72	48	-194	371
150	1	2.5	-48	-77	53	-219	354
175	1.1	2.7	-51	-81	58	-241	338
200	1.1	2.8	-53	-84	63	-260	324
225	1.2	2.8	-54	-87	67	-278	311
250	1.2	2.9	-55	-88	70	-294	299
275	1.2	2.9	-56	-89	73	-308	288
300	1.2	3	-57	-91	78	-316	289
International tourism in a CO ₂ -constrained world							
25	1.7	3.9	-5	-7	10	-26	288
50	3.1	7	-8	-13	20	-46	282
75	4.3	9.6	-11	-17	28	-63	278
100	5.3	11.8	-14	-21	36	-77	274
125	6.1	13.7	-16	-24	44	-89	270
150	6.9	15.3	-17	-27	51	-100	267
175	7.5	16.7	-19	-29	58	-109	264
200	8.1	17.9	-20	-31	64	-117	261
225	8.6	19	-21	-32	70	-125	258
250	9.1	20	-22	-34	76	-132	256
275	9.5	20.9	-23	-35	82	-138	254
300	9.9	21.7	-24	-36	88	-144	251
International trade and tourism in a CO ₂ -constrained world							
25	-	-	-20	-31	23	-77	405
50	-	-	-34	-55	44	-142	386
75	-	-	-46	-72	61	-196	369
100	-	-	-54	-86	77	-242	353
125	-	-	-61	-96	91	-283	339
150	-	-	-66	-104	104	-318	327
175	-	-	-70	-110	116	-350	315
200	-	-	-73	-115	127	-378	305
225	-	-	-75	-119	137	-403	295
250	-	-	-77	-122	147	-426	286
275	-	-	-78	-124	156	-446	278
300	-	-	-81	-128	166	-460	277

Notes: The base year for calculations is 2014 using data and input parameters as specified in Table 6.1 and $\epsilon^I = -7$ and $\epsilon^T = -6$.

Appendix D

Correspondence tables

D.1 Aggregation of extra-EU data into industries

#	Industry	NST/R three digit code and description	
Energy			
1	Crude petroleum	310	Crude petroleum
2	Gaseous hydrocarbons	330	Gaseous hydrocarbons, liquid or compressed
3	Coal, lignite and peat	211	Coal
		213	Coal briquettes
		221	Lignite
		223	Lignite briquettes
		224	Peat
Mining and quarrying			
4	Iron ore	410	Iron ore and concentrates; except roasted iron pyrites
5	Minor bulk	452	Copper ore and concentrates; copper matte
		453	Bauxite and concentrates
		455	Manganese ore and concentrates
		459	Other non-ferrous ores and concentrates
		611	Sand for industrial use
		612	Ordinary sand and gravel
		613	Pumice stone, including pumiceous sand and gravel
		621	Salt, crude or refined
		622	Unroasted iron pyrites
		623	Sulphur
		634	Chalk
		639	Other crude minerals
		711	Sodium nitrate, natural
		712	Phosphates, crude, natural
		713	Potassium salts, crude, natural
		719	Other natural fertilizers
		820	Aluminium oxide and hydroxide
Agriculture and forestry			
6	Grain	11	Wheat, spelt and meslin
		12	Barley
		13	Rye
		14	Oats
		15	Maize
		16	Rice

Continued on next page

Table D.1 – continued from previous page

Table D.1 Continued from previous page			
#	Industry	NST/R three digit code and description	
7	Fruits and vegetables	19	Other cereals n.e.s.
		20	Potatoes
		31	Citrus fruit
		35	Other fruit and nuts, fresh
		39	Other vegetables, fresh or frozen
8	Wood and cork	60	Sugar beets
		51	Paper pulp wood
		52	Pit props
		55	Other wood in the round
		56	Railway or tramway sleepers of wood and other wood roughly squared, half squared, or sawn
		57	Fuel wood, wood charcoal, wood waste, cork unworked, waste cork
Manufacturing			
9	Manufacture of food products	141	Meat, fresh, chilled or frozen
		147	Meat, dried, salted, smoked; prepared or preserved meat
		142	Fish, crustaceans and molluscs, fresh, frozen, dried, salted or smoked
		148	Fish, crustaceans and molluscs, prepared or preserved
		164	Fruit, frozen, dried, dehydrated; prepared and preserved fruit
		165	Dried vegetables
		166	Prepared and preserved vegetables
		182	Animal and vegetable fats and oils, and products derived therefrom
		145	Margarine, lard and edible fats
		144	Butter, cheese, other dairy produce
		161	Flour, cereal meal and groats
		895	Starches and gluten
		163	Other cereal preparations
		112	Refined sugar
		136	Glucose, dextrose; other sugars; sugar confectionery; honey
		132	Cocoa and chocolate
		133	Tea, mat+, spices
		131	Coffee
		139	Food preparations n.e.s.
10	Manufacture of beverages	121	Wine of fresh grapes, grape must
		122	Beer made from malt
		125	Other alcoholic beverages
		128	Non-alcoholic beverages
11	Manufacture of tobacco products	135	Manufactured tobacco
12	Manufacture of textiles	962	Textile yarn, fabrics, made-up articles and related products
13	Manufacture of wearing apparel and leather	961	Leather, manufactures of leather, of raw hide and skins
		963	Travel goods, clothing, knitted and crocheted goods, footwear
14	Manufacture of wood and of products of wood and cork	976	Wood and cork manufactures, excluding furniture
15	Manufacture of paper and paper products	972	Paper and paperboard, unworked
		973	Paper and paperboard manufactures
		974	Paper matter
		841	Paper pulp
16	Manufacture of coke and refined petroleum products	231	Coke and semi-coke of coal
		233	Coke and semi-coke of lignite

Continued on next page

Continued on next page

Table D.1 – continued from previous page

#	Industry	NST/R three digit code and description	
17	Manufacture of chemicals and chemical products	321	Motor spirit
		323	Kerosene, jet fuel and white spirit
		325	Distillate fuels
		327	Residual fuel oils
		341	Lubricating oils and greases
		343	Petroleum bitumen and bituminous mixtures
		349	Other non-fuel petroleum derivatives
		811	Sulphuric acid; oleum
		812	Caustic soda and soda lye
		813	Sodium carbonate (soda ash)
		814	Calcium carbide
		819	Other basic chemicals
		721	Basic slag (thomas slag)
		722	Other phosphatic fertilizers
		723	Potassic fertilizers
		724	Nitrogenous fertilizers
		729	Composite and other manufactured fertilizers
		896	Other chemical products and preparations
		892	Dyeing, tanning and colouring materials
18	Manufacture of basic pharmaceutical products and pharmaceutical preparations	894	Manufactured explosives, fireworks and other pyrotechnic articles, sporting ammunition
		43	Man-made fibres
		893	Medicinal and pharmaceutical products; perfumery and cleansing preparations
19	Manufacture of rubber and plastic products	971	Semi-finished products and manufactured articles of rubber
20	Manufacture of other non-metallic mineral products	891	Plastic materials, unworked
		951	Glass
21	Manufacture of basic metals and fabricated metal products	952	Glassware, pottery and other manufactures of minerals
		692	Bricks, roofing tiles and other ceramic building materials, refractory building materials
		614	Clay and clay earth
		631	Crushed or broken stone; pebbles, macadam, tarred macadam
		641	Cement
		642	Lime
		650	Plasters
		691	Pumice stone agglomerates; concrete, cement and similar building materials
		512	Pig iron, spiegeleisen and carburized ferro-manganese
		513	Ferro-alloys other than carburized ferro-manganese (non-ecsc)
		515	Crude steel
		522	Semi-finished rolled steel products (blooms, billets, slabs, sheet bars, coils)
		523	Other semi-finished steel products (non-ecsc)
		532	Hot-rolled or -shaped steel
		533	Cold-rolled or -shaped or forged steel (non-ecsc)
		535	Wire rod
		536	Steel iron and steel wire (non-ecsc)
		542	Sheets and plates of steel for re-rolling; universal plates
		543	Other steel plates and sheets (non-ecsc)
		545	Steel hoop and strip, tinplate

Continued on next page

Table D.1 – continued from previous page

#	Industry	NST/R three digit code and description	
		546	Other steel hoop and strip (non-ecsc)
		551	Tubes, pipes and fittings
		552	Iron and steel castings and forgings
		561	Copper and copper alloys, unwrought
		562	Aluminium and aluminium alloys, unwrought
		563	Lead and lead alloys, unwrought
		564	Zinc and zinc alloys, unwrought
		565	Other non-ferrous metals and alloys thereof, unwrought
		568	Finished and semi-finished products of non-ferrous metals (except manufactures)
		941	Finished structural parts and structures
		949	Other manufactures of metal
22	Manufacture of electronic and eletrical equipment	931	Electrical machinery, apparatus, appliances and engines; parts thereof
23	Manufacture of machinery, vehicles and other transport equipment	920	Tractors; agricultural machinery and equipment, whether or not assembled; parts thereof
		939	Non-electrical machinery, apparatus, appliances and engines; parts thereof
		910	Transport equipment, whether or not assembled, parts thereof
24	Manufacture of furniture	975	Furniture, new
Other			
25	Live animals	1	Live animals
26	Gold, coins, medals	994	Gold, coins, medals

D.2 Aggregation of OECD-MTC data into industries

#	Industry	HS2	HS6	HS2/HS6 description
Energy				
1	Crude petroleum		2709	Crude oil from petroleum and bituminous minerals
2	Gaseous hydrocarbons		2705	Coal gas, water gas, prdcr gas etc
			2711	Petroleum gases & other gaseous hydrocarbons
3	Coal, lignite and peat		2701	Coal, briquettes, ovoids etc
			2702	Lignite, agglomerated or not, excluding jet
			2703	Peat (including peat litter), incl agglomrtd
			2704	Coke etc of coal, lignite or peat, retort carbon
			4402	Wood charcoal, whether or not agglomerated
Mining and quarrying				
4	Iron ore		2601	Iron ores & concentrates, including roast pyrites
5	Minor bulk	25		Salt; sulphur; earths and stone; plastering materials, lime and cement
			2602	Manganese ores & concentrates inc mangnfrs iron ores
			2603	Copper ores and concentrates
			2604	Nickel ores and concentrates
			2605	Cobalt ores and concentrates
			2606	Aluminum ores and concentrates
			2607	Lead ores and concentrates
			2608	Zinc ores and concentrates

Continued on next page

Table D.2 – continued from previous page

#	Industry	HS2	HS6	HS2/HS6 description
			2609	Tin ores and concentrates
			2610	Chromium ores and concentrates
			2611	Tungsten ores and concentrates
			2612	Uranium or thorium ores and concentrates
			2613	Molybdenum ores and concentrates
			2614	Titanium ores and concentrates
			2615	Niobium, tantalum, vanadium & zirconium ore & conc
			2616	Precious metal ores and concentrates
Agriculture and forestry				
7	Grain	10		Cereals
8	Fruits and vegetables	7		Edible vegetables and certain roots and tubers
		8		Edible fruit and nuts; peel of citrus fruit or melons
6	Wood and cork		4401	Fuel wood in logs etc, wood in chips, etc
			4403	Wood in the rough, stripped or not of sapwood etc
			4501	Natural cork, raw or simply prep, waste cork etc
			4502	Natural cork deback/rgh sqd in blocks/sheets/strips
Manufacturing				
9	Manufacture of food products	2		Meat and edible meat offal
		3		Fish and crustaceans, molluscs and other aquatic invertebrates
		4		Dairy produce; birds' eggs; natural honey etc
		5		Products of animal origin, not elsewhere specified or included
		9		Coffee, tea, mate and spices
		11		Products of the milling industry; malt; starches; inulin; wheat gluten
		13		Lac; gums, resins and other vegetable saps and extracts
		14		Vegetable plaiting materials/products not elsewhere included
		15		Animal or vegetable fats and oils and their cleavage products etc
		16		Preparations of meat, of fish or of crustaceans, molluscs etc
		17		Sugars and sugar confectionery
		18		Cocoa and cocoa preparations
		19		Preparations of cereals, flour, starch or milk; pastrycooks' products
		20		Preparations of vegetables, fruit, nuts or other parts of plants
		21		Miscellaneous edible preparations
		35		Albuminoidal substances; modified starches; glues; enzymes
10	Manufacture of beverages	22		Beverages, spirits and vinegar
11	Manufacture of tobacco products	24		Tobacco and manufactured tobacco substitutes
12	Manufacture of textiles	50		Silk
		51		Wool, fine or coarse animal hair; horsehair yarn and woven fabric
		52		Cotton
		53		Other vegetable textile fibres; paper yarn and woven fabrics of paper yarn
		56		Wadding, felt and nonwovens; special yarns etc
		57		Carpets and other textile floor coverings
		58		Special woven fabrics; tufted textile fabrics etc
		59		Impregnated, coated, covered or laminated textile fabrics etc
		60		Knitted or crocheted fabrics

Continued on next page

Table D.2 – continued from previous page

#	Industry	HS2	HS6	HS2/HS6 description
13	Manufacture of wearing apparel and leather	63		Other made up textile articles; sets; worn clothing and worn textile articles
		41		Raw hides and skins (other than furskins) and leather
		42		Articles of leather; saddlery and harness; travel goods, handbags etc
		43		Furskins and artificial fur; manufactures thereof
		61		Articles of apparel and clothing accessories, knitted or crocheted
		62		Articles of apparel and clothing accessories, not knitted or crocheted
		64		Footwear, gaiters and the like; parts of such articles
		65		Headgear and parts thereof
14	Manufacture of wood and of products of wood and cork		4404	Hoopwood, split poles, pickets and stakes etc
			4405	Wood wool (excelsior), wood flour
			4406	Railway or tramway sleepers (cross-ties) of wood
			4407	Wood sawn or chipped length, sliced etc, ovmm thick
			4408	Veneer sheets etc, not over mm thick
			4409	Wood, continuously shaped (tongued, grooved etc)
			4410	Particle board & similar board of wood etc
			4411	Fiberboard of wood or other ligneous materials
			4412	Plywood, veneered panels & similar laminated wood
			4413	Densified wood blocks/plates/strips/profile shapes
			4414	Wooden frames paintings, photographs, mirrors, etc
			4415	Packing cases etc of wood, pallets etc of wood
			4416	Casks, barrels, vats, etc and parts, of wood
			4417	Tools, tool & broom bodies etc shoe last/trees wood
			4418	Builders' joinery and carpentry of wood
			4419	Tableware and kitchenware, of wood
			4420	Wood marquetry etc, jewel case etc & wood furn nesoi
			4421	Articles of wood, nesoi
			4503	Articles of natural cork
			4504	Agglomerated cork and articles thereof
15	Manufacture of paper and paper products	47		Pulp of wood or of other fibrous cellulosic material; recovered paper
		48		Paper and paperboard; articles of paper pulp, of paper or of paperboard
		49		Printed books, newspapers, pictures etc
16	Manufacture of coke and refined petroleum products		2706	Mineral tars, including reconstituted tars
			2707	Oils etc from high temp coal tar, sim aromatic etc
			2708	Pitch & pitch coke from coal tar or other min tars
			2710	Oil (not crude) from petrol & bitum mineral
			2712	Petroleum jelly, mineral waxes & similar products
			2713	Petroleum coke, petroleum bitumen & other residues
			2714	Bitumen & asphalt, natural, shale & tar sands etc
			2715	Bit mixture from nat asph, nat bit, pet bit, min tar or pt
17	Manufacture of chemicals and chemical products	28		Inorganic chemicals; organic or inorganic compounds
		29		Organic chemicals
		31		Fertilisers

Continued on next page

Table D.2 – continued from previous page

#	Industry	HS2	HS6	HS2/HS6 description
		32		Tanning or dyeing extracts; tannins and their derivatives
		33		Essential oils and resinoids; perfumery, cosmetic or toilet preparations
		34		Soap, organic surface-active agents, washing preparations, etc
		36		Explosives; pyrotechnic products etc
		38		Miscellaneous chemical products
		54		Man-made filaments
		55		Man-made staple fibres
18	Manufacture of basic pharmaceutical products and pharmaceutical preparations	30		Pharmaceutical products
19	Manufacture of rubber and plastic products	39		Plastics and articles thereof
		40		Rubber and articles thereof
20	Manufacture of other non-metallic mineral products	68		Articles of stone, plaster, cement, asbestos, mica or similar materials
		69		Ceramic products
		70		Glass and glassware
21	Manufacture of basic metals and fabricated metal products	72		Iron and steel
		73		Articles of iron or steel
		74		Copper and articles thereof
		75		Nickel and articles thereof
		76		Aluminium and articles thereof
		78		Lead and articles thereof
		79		Zinc and articles thereof
		80		Tin and articles thereof
		81		Other base metals; cermets; articles thereof
		82		Tools, implements, cutlery, spoons and forks, of base metal
		83		Miscellaneous articles of base metal
22	Manufacture of electronic and electrical equipment	85		Electrical machinery and equipment and parts thereof
23	Manufacture of machinery, vehicles and other transport equipment	84		Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof
		86		Railway or tramway locomotives, rolling-stock and parts
		87		Vehicles other than railway or tramway rolling-stock, and parts thereof
		88		Aircraft, spacecraft, and parts thereof
		89		Ships, boats and floating structures
24	Manufacture of furniture	94		Furniture; bedding, mattresses, mattress supports, cushions and similar
Other				
25	Live animals	1		Live animals
26	Gold, coins, medals	71		Natural or cultured pearls, precious or semi-precious stones, precious metals
		91		Clocks and watches and parts thereof
		92		Musical instruments; parts and accessories of such articles